HYDROLOGY OF MAJOR ESTUARIES AND SOUNDS OF NORTH CAROLINA

U. S. GEOLOGICAL SURVEY
WATER RESOURCES INVESTIGATIONS 79-46

PREPARED IN COOPERATION WITH THE
NORTH CAROLINA DEPARTMENT OF NATURAL
RESOURCES AND COMMUNITY DEVELOPMENT

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle HYDROLOGY OF MAJOR ESTUARIES AND SOUNDS OF NORTH CAROLINA			5. Report Date July 1979 6.
7. Author(s) G. L. Giese, H. B. Wilder, and G. G. Parker, Jr.			8. Performing Organization Rept. No. USGS/WRI-79-46
9. Performing Organization Name and Address U.S. Geological Survey Water Resources Division P. O. Box 2857 Raleigh, N.C. 27602			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey Water Resources Division P. O. Box 2857 Raleigh, N.C. 27602			13. Type of Report & Period Covered Final 1967-1978 14.

15. Supplementary Notes

Prepared in cooperation with the North Carolina Department of Natural Resources and Community Development

16. Abstracts

Knowledge of the basic hydrology of North Carolina's major estuaries and sounds is necessary to help solve hydrology-related estuarine problems which include contamination of some estuaries with municipal and industrial wastes and drainage from adjacent intensively-farmed areas, nuisance-level algal blooms, excessive shoaling in some navigation channels, saltwater intrusion into usually fresh estuarine reaches, too-high or too-low salinities in nursery areas for various estuarine species, and flood damages due to hurricanes.

Saltwater intrusion occurs from time to time in all major estuaries except the Roanoke River, where releases from Roanoke Rapids Lake and other reservoirs during otherwise low-flow periods effectively block saline water from the estuary.

17. Key Words and Document Analysis. 17a. Descriptors

*Tides, *Saline water intrusion, *Saline water-freshwater interface, *Stratification, Salt marshes, North Carolina, *Flow characteristics, Wind tides, *Water chemistry, *Sedimentation.

17b. Identifiers/Open-Ended Terms

*Albemarle Sound, *Pamlico Sound, *Cape Fear River, *Northeast Cape Fear River, *Neuse River, *Trent River, *Tar River, *Pamlico River, *Chowan River, *Roanoke River, *Tidal hydraulics.

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 189
No restriction on distribution	20. Security Class (This Page UNCLASSIFIED	22. Price

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Department of Natural Resources
and Community Development*

July 1979

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

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Raleigh, North Carolina 27602

July 1979

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COVER: Harbor at Wanchese, North Carolina; drawing by Libby Giese from copyrighted photograph by Bill Patterson (by permission of Braxton Flye, editor *North Carolina Coastal Fishing and Vacation guide*)

INTERNATIONAL SYSTEM UNITS

The following factors may be used to convert the U.S. customary units published in this report to the International System of Units (SI).

Multiply U.S. customary unit	By	To obtain SI (metric) unit
	Length	
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
	Area	
square feet (ft^2)	.0929	square meters (m^2)
square miles (mi^2)	2.590	square kilometers (km^2)
acre	4,047	square meters (m^2)
	Volume	
cubic yards (yd^3)	.764	cubic meters (m^3)
acre-feet	1,233	cubic meters (m^3)
	Flow	
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
cubic feet per second per square mile [$(ft^3/s)/mi^2$]	.01093	cubic meters per second per square kilometer [$(m^3/s)/km^2$]
	Velocity	
feet per second (ft/s)	.3048	meters per second (m/s)
miles per hour (mi/hr)	1.609	kilometers per hour (km/hr)
	Mass	
pounds (lb avoirdupois)	.4536	kilograms (kg)
ton (short, 2,000 lbs)	.9072	tonne (t)

HYDROLOGY OF MAJOR ESTUARIES AND SOUNDS OF NORTH CAROLINA

By G. L. Giese, H. B. Wilder, and G. G. Parker, Jr.

ABSTRACT

Hydrology-related problems associated with North Carolina's major estuaries and sounds include contamination of some estuaries with municipal and industrial wastes and drainage from adjacent intensively-farmed areas, and nuisance-level algal blooms. In addition, there is excessive shoaling in some navigation channels, saltwater intrusion into usually fresh estuarine reaches, too-high or too-low salinities in nursery areas for various estuarine species, and flood damage due to hurricanes.

The Cape Fear River is the only major North Carolina estuary having a direct connection to the sea. Short-term flow throughout most of its length is dominated by ocean tides. The estuarine reaches of the Neuse-Trent, Tar-Pamlico, Chowan, and Roanoke River systems are at least partly shielded from the effects of ocean tides by the Outer Banks and the broad expanses of Pamlico and Albemarle Sounds. With the probable exception of the Roanoke River, winds are usually the dominant short-term current-producing force in these estuaries and in most of Pamlico and Albemarle Sounds.

Freshwater entering the major estuaries is, where not contaminated, of acceptable quality for drinking with minimum treatment. However, iron concentrations in excess of 0.3 milligrams per liter sometimes occur and water draining from swampy areas along the Coastal Plain is often highly colored, but these problems may be remedied with proper treatment. Nuisance-level algal blooms have been a recurring problem on the lower estuarine reaches of the Neuse, Tar-Pamlico, and Chowan rivers where nutrients (compounds of phosphorous and nitrogen) are abundant. The most destructive blooms tend to occur in the summer months during periods of low freshwater discharge and relatively high water temperatures.

Saltwater intrusion occurs from time to time in all major estuaries except the Roanoke River, where releases from Roanoke Rapids Lake and other reservoirs during otherwise low-flow periods effectively block saline water from the estuary. Salinity stratification is common in the Cape Fear and Northeast Cape Fear Rivers, but is less common in other estuaries which do not have direct oceanic connections and where wind is usually effective in mixing with depth. The greatest known upstream advance of the saltwater front (200 milligrams per liter chloride) in most North Carolina estuaries occurred during or in the aftermath of the passage of Hurricane Hazel on October 15, 1954. Hurricane Hazel ended an extreme drought when many North Carolina rivers were at or near minimum recorded flows. Consequently, saltwater intrusions in many North Carolina estuaries were at or near the maximums ever known to have occurred. When the hurricane struck, high storm tides along the coast drove saline water even further upstream in many localities. The probability of two such rare events happening concurrently is not known, but the recurrence interval may be reckoned in hundreds of years.

New shoaling materials found in the lower channelized reaches of the Cape Fear and Northeast Cape Fear Rivers are primarily derived, not from upstream sources, but from nearby shore erosion, from slumping of material adjacent to the channels, from old spoil areas, or from ocean-derived sediments carried upstream by near-bottom density currents. It is not known at this time whether this holds true for other estuaries discussed in this report.

INTRODUCTION

The estuaries and sounds of North Carolina are among the State's most valuable resources. They serve as routes for low cost transportation by means of ships and barges, as sources of large amounts of water for industrial and, where not too salty, for municipal use. They also serve as both fisheries and nurseries for a wide variety of marine life, and as focal points for recreational activities. Planning for optimum use of the estuaries for these sometimes conflicting uses depends in part on having detailed knowledge of the physical and chemical processes at work in them. Problems which have arisen in connection with the uses of North Carolina estuaries and sounds include (1) contamination of some estuaries with municipal and industrial wastes and drainage from adjacent intensively-farmed areas, (2) excessive shoaling in some navigation channels, (3) in nursery areas, too-high salinities due to low fresh-water inflow or too-low salinities due to high fresh-water inflow, (4) occasional fish kills related to contamination or deoxygenation of estuarine waters, (5) nuisance-level algal blooms in some estuaries, and (6) flood damages from unusually high hurricane-induced tides.

The approximate extent of North Carolina's Sounds and estuaries is shown in figure A, and plate 1 summarizes conditions of maximum upstream saltwater encroachment and tide effects for major estuaries. These estuaries are in an area which many feel is experiencing the leading edge of a wave of agricultural, commercial, and recreational development. To minimize possible adverse effects of development and maximize benefits, management decisions related to development should be predicated, at least in part, on a basic understanding of the present hydrology of North Carolina's estuarine waters. Often, this information has been lacking or inconvenient to gather when decisions must be made. The purpose of this report is to summarize current basic knowledge of the hydrology of the major estuaries and sounds in North Carolina, not only for use in management decisions now, but also for use as a general information source for other current and future estuarine studies in hydrology and related fields.

This report was prepared by the U.S. Geological Survey in cooperation with the North Carolina Department of Natural Resources and Community Development and is based partly on data and interpretive reports originating from the Geological Survey and partly on data and interpretive reports originating from other Federal, State, local, and private sources. These sources are acknowledged in the text where appropriate.

This summary report, while fairly complete with respect to work done by the Geological Survey, is much less so for work done by other public and private agencies. To summarize all the vast accumulated body of hydrology-related work done by others is beyond the scope of this report. Rather, the intent here is to present a basic picture of the hydrology of the major estuaries and sounds in North Carolina in terms of freshwater inflow, tide-affected flow, water levels, freshwater quality, salinity, and sedimentation - utilizing Geological Survey data where available, but filling gaps where possible with information from other agencies.

This report is divided into four chapters. The first, General Hydrology, is primarily a discussion of basic hydrologic principles relating to tides, tidal flow, salinity, sedimentation, and the effects of winds and hurricanes. The other three chapters summarize present knowledge of the hydrology of individual sounds and estuaries in each of three estuarine systems. The estuarine systems are, in order of discussion, the Cape Fear River system, the Pamlico Sound system, and the Albemarle Sound system. The comprehensiveness of the summaries for each sound or estuary is directly related to the availability of information on which the summaries are based. The Cape Fear River estuary, for example, has been much more thoroughly studied than the Roanoke River. In general, the larger the estuary, the more complete is the information available.

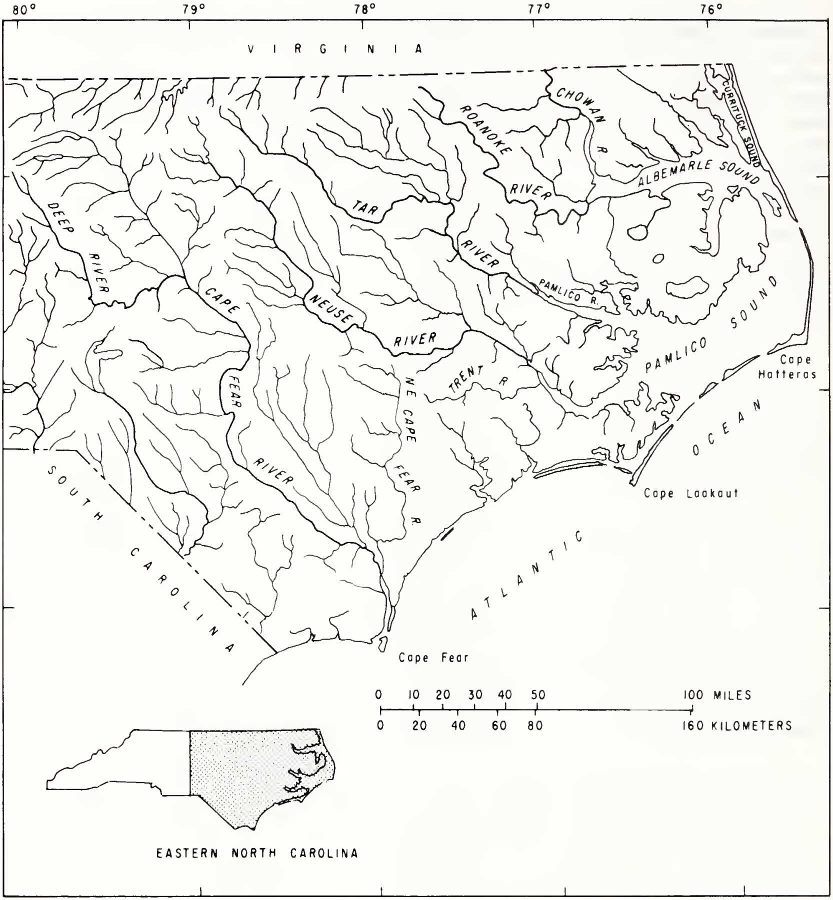


Figure A.--Drainage network of eastern North Carolina and approximate extent of estuaries and sounds.

The Cape Fear River estuarine system includes the Cape Fear River estuary and the Northeast Cape Fear River estuary. These are unique among major North Carolina estuaries in that they have a direct connection with the ocean. The Pamlico Sound estuarine system comprises Pamlico Sound, the Neuse River estuary, the Trent River estuary, the Pamlico River estuary, and a number of lesser estuaries which enter Pamlico Sound. These are characterized by large channels, small lunar tides, and by flow which is greatly affected by winds.

The Albemarle Sound system comprises Albemarle Sound, Currituck Sound, and those estuaries draining into Albemarle Sound, the largest of which are the Roanoke River and the Chowan River estuaries. These are also characterized by small lunar tides and, with the possible exception of the Roanoke Estuary, by the fact that wind exerts a dominant short-term influence on water levels and water movement.

CHAPTER 1

GENERAL HYDROLOGY

A sound is formally defined as a relatively narrow passage of water, too wide and extensive to be called a strait, that connects two water bodies, or it can be a channel passing between a mainland and an island. A sound is also sometimes thought of as an inlet, arm, or recessed portion of the sea. This last definition comes closest to describing Pamlico and Albemarle sounds, but even it is not entirely satisfactory. Thus, it may be that the term sound as applied to North Carolina's sounds is a misnomer, but no more formally correct term is available. The term estuary, as used in this report, is that part of the lower course of a coastal river affected by ocean tides.

Flow of water in an estuary can be described as the superposition of tidal flow on the otherwise unaffected freshwater discharge of the estuary. In the lower reaches of an estuary, average flow due to tides may be many times the flow due to freshwater inflow. However, flow due to tides is cyclic and in the North Carolina area is semidiurnal, changing direction every six hours and twelve minutes (6.22 hrs). Over a number of tidal cycles, the flow component from tides averages out to be practically zero, whereas the flow component from freshwater inflow, although it may be smaller, always acts in a downstream direction and controls long-term average flow in an estuary.

Saline or salty water in an estuary moves upstream and downstream in response to tidal action, freshwater outflow, and turbulent mixing. In discussing this movement, it is convenient to select an arbitrary value of salinity, the location of which represents the upstream limit of the zone of saltwater mixing, which we will refer to as the saltwater front. In this report a value of 200 mg/L of chloride is used to establish the saltwater front because that concentration clearly indicates the presence of some seawater, and water with less than this amount is usable for most purposes.

Seasonal ranges in movement of the saltwater front are primarily caused by seasonal changes in freshwater inflow and commonly are greater than daily ranges due to tides alone. In the Cape Fear River, for instance, the seasonal range due to freshwater inflow is typically 15 miles or more, whereas the range due to tides is only about 3 to 6 miles.

This seasonal movement of the saltwater front is basically the product of two opposing processes. The saltwater front tends to be displaced downstream by incoming freshwater. On the other hand, the more dense saltwater tends to move upstream by mixing and diffusion of

salty water with fresher water upstream. If these two processes are roughly in balance, there will be little net movement of the front. When freshwater inflows are high, then the tendency towards downstream displacement of the front by incoming freshwater overwhelms the tendency towards upstream movement due to mixing and diffusion. When freshwater inflows are low, the opposite is true.

During and immediately after periods of low freshwater inflow, which typically occur in the late summer and fall in North Carolina, the landward encroachment of the saltwater front is usually at its greatest for the year. Another factor which can contribute somewhat to greater encroachment at this time of the year is that mean tidal level may be several tenths of a foot higher during November than, say, during July. In the winter and spring months, when freshwater inflow is high, displacement of the saltwater front seaward is usually at its annual maximum.

Ocean Tides

The drivirg force in the regular, periodic fluctuations in estuarine stage, discharge, and movement of the saltwater front is ocean tides. Although the word "tide" has often been used rather loosely to include water-level fluctuations caused by other forces, such as wind and barometric pressure, it is considered in this report to include only those water-level phenomena caused by the gravitational attractions of the moon and the sun acting on the earth. The movements of the earth, moon, and sun relative to each other occur in cycles which, while complex, are predictable and repetitive. This, in turn, results in tides which occur in cycles that are also complex, but predictable and repetitive.

Actually, the rise and fall of the water and the accompanying currents should be dealt with together, because they are only different manifestations of the same phenomenon, a tide wave. However, for practical reasons, they are often dealt with separately, and the common English usage is to refer to the rise and fall of the water level as the tide, and to the accompanying currents as tidal currents.

The tidal forces can be separated into a number of components called partial tides. The principal partial tides are listed in table 1.1. The partial tides are characterized by their periods and a coefficient directly related to the magnitude of the partial-tide producing force. The partial-tide forces, when plotted against time, produce sine-like curves of various magnitudes and periods which alternately reinforce, then interfere with, one another. The resultant of all these partial-tide forces is a series of alternating high and low tides of varying magnitudes having a period of 12.42 hours.

Table 1.1.--The ten most important partial tides. (Adapted from Schureman, 1924.)

Name of corresponding partial tide	Period, in hours	Coefficient
Semidiurnal:		
Principal lunar	12.42	0.4543
Principal solar	12.00	.2120
Larger lunar elliptic	12.66	.0880
Luni-solar	11.97	.0576
Diurnal:		
Luni-solar	23.93	.2655
Principal lunar	25.82	.1886
Principal solar	24.07	.0880
Long-period:		
Lunar fortnightly	327.86	.0783
Lunar monthly	661.30	.0414
Solar semi-monthly	2191.43	.0365

Figure 1.1 is a graph of predicted high and low tides for August 9-22, 1977, for the Cape Fear River estuary at Wilmington, North Carolina. It clearly shows diurnal inequalities in the heights of the two high and two low tides each day. These are caused principally by the interaction of the several semidiurnal (twice daily) and diurnal (daily) partial tides (fig. 1.2). The diurnal partial tide reinforces one of the semi-diurnal tides and interferes with the other, thus producing the diurnal inequalities.

When the range between high and low tide is largest, the tides are called spring tides; when the range is smallest, they are called neap tides. The recurrence interval of spring tides and neap tides is 14.3 days. They are primarily caused by the interaction of the principal lunar and principal solar semidiurnal tides. These have slightly different periods (12.42 and 12.00 hours, respectively) which result in alternatingly reinforcing then interfering with each other in cycles which take 14.3 days to complete. The juxtaposition of the two tide components during spring tide and neap tide is illustrated in figure 1.3. During spring tide the two components are nearly in phase with one another; during neap tide the two are almost completely out of phase. The results of this interaction are also illustrated in figure 1.1, which shows that the range between predicted high and low tides during August 15-18 was greater than that during August 9-11.

The long-period partial tides listed in table 1.1 are not as important as the semidiurnal and diurnal components in controlling tide heights but may make a difference of about 0.5 foot seasonally in tide heights. The effects of these long-period partial tides are incorporated into tide predictions of the National Ocean Survey. In addition, allowances are made in these predictions for differences in seasonal tide heights due to increasing or decreasing freshwater inflow in estuaries. These differences may be more than a foot in some estuaries. The National Ocean Survey annually publishes tide height and current predictions for a number of North Carolina coastal locations.

Estuarine Flow

As mentioned earlier, flow of water in an estuary can be described as the superposition of tidal flow on the normal downstream river flow. Knowledge of the rates of movement of estuarine waters and how rates and direction of movement vary are of great importance in aiding navigation, predicting the manner of movement and dispersion of pollutants, and in understanding sedimentation characteristics. The purpose of this section of the report is to describe the most important aspects of estuarine flow.

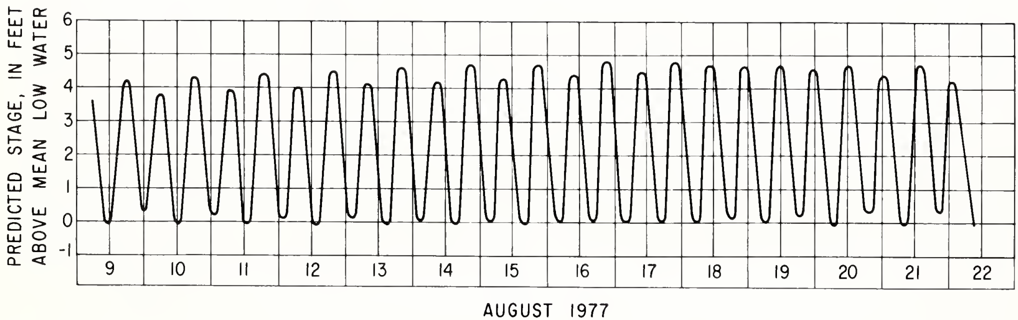


Figure 1.1.--Tide curve for Cape Fear River estuary at Wilmington for Aug. 9-22, 1977, based on predicted times and heights of high and low water from National Ocean Survey, Tide Tables.

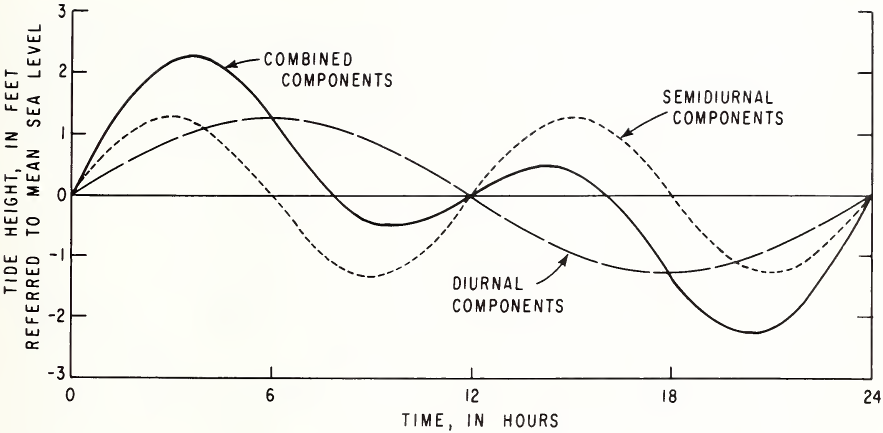


Figure 1.2.--Diurnal inequalities produced from interaction of semidiurnal and diurnal tidal components. Adapted from Sverdrup, Johnson, and Fleming, 1942.

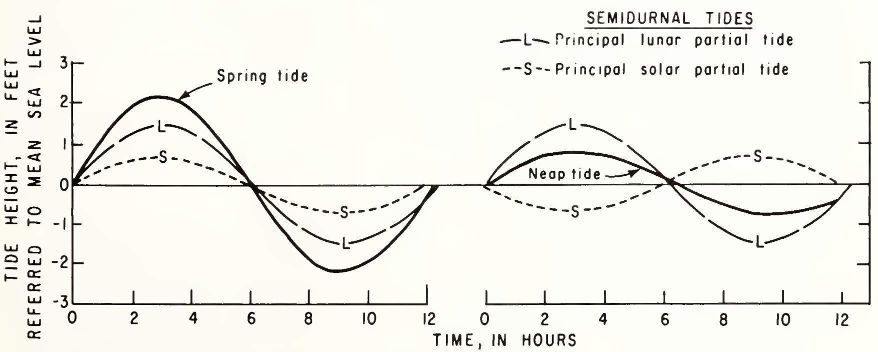


Figure 1.3.--Tide curves at spring tide and neap tide. Adapted from Sverdrup, Johnson, and Fleming, 1942.

The combination of river flow and tidal flow will be referred to as tide-affected flow in this report. Tide waves associated with the tidal component of flow may have wave lengths of several hundred miles or more. When we realize that most estuaries are much shorter than this, it is clear that most estuaries can be occupied by only part of a tide wave at any given time. The behavior of an idealized tide wave in an estuary is illustrated in figure 1.4, which shows how water velocity

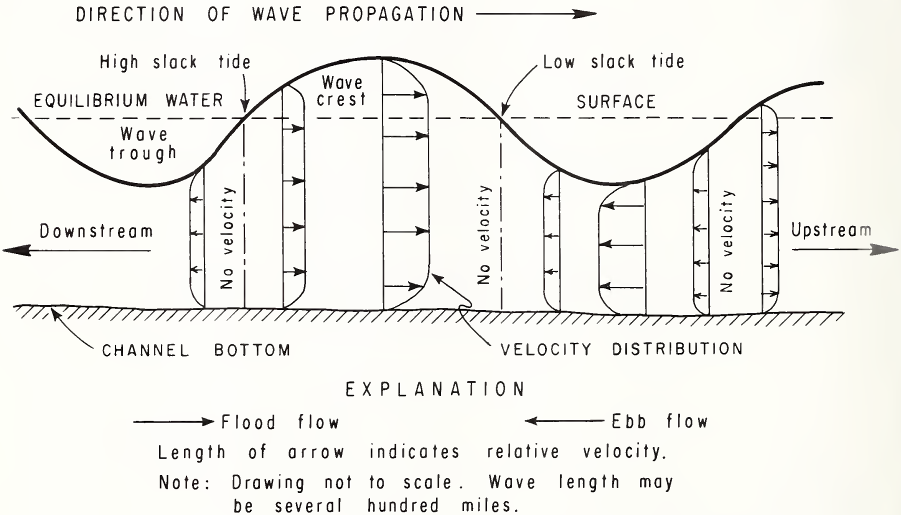


Figure 1.4.--Behavior of an idealized tide wave in an estuary.

varies along the profile of a tide wave propagating along a channel. The wave here is idealized in that it has assumed symmetry, is propagating in a fluid of homogeneous density, is free from the effects of internal and boundary friction, and is propagating without opposition from freshwater inflow, barriers or any other flow obstruction. Note that the direction of horizontal water movement at the wave crest is always in the direction of wave propagation; at the wave troughs it is in the opposite direction. Horizontal velocity is zero halfway between the crests and troughs, and is maximum at the crests and troughs.

Several other interesting facts may be derived from figure 1.4. First, times of zero velocity do not coincide with times of high and low tide, as common sense might suggest. Rather, times of zero velocity (slack tides) occur about halfway between times of high and low tides. Second, water in a tide wave may flow up-gradient, that is, the water surface may be sloping downstream where the flow is upstream.

When the effects of freshwater inflow, friction, and any barriers (such as dams) are superimposed on the flow pattern of an idealized tide wave, velocity distributions relative to the crests and troughs are modified. Freshwater inflow, for example, will not affect the time of occurrence of high or low tide, but will result in high-water slack occurring earlier than otherwise and low-water slack occurring later than otherwise. Thus, as freshwater inflow increases, high-water slack will occur closer in time to high tide. Also, the closer to the head of tide (or to a dam) one is, the nearer in time are high water and high-water slack. Thus, in real estuaries, the above factors may considerably alter the velocity distribution along a tide wave from what might be predicted based on the idealized situation portrayed in figure 1.4. (See later discussion of measurements of tide-affected flow in the Cape Fear and Northeast Cape Fear Rivers).

The wave form itself propagates. The speed with which it propagates is referred to as wave celerity and is equal to $\sqrt{gh}$, where g is the gravitational constant and h is the depth of the water in which the wave is propagating. Thus, one can calculate the difference in time between occurrence of high or low tide at different points along a total reach of known depth. An important point here is that the wave celerity does not refer to the velocities of individual water particles, but only to the wave form. Actually, the wave form propagates much faster than individual water particles can move.

Freshwater inflow to an estuary opposes the flood-tide flow and reinforces the ebb-tide flow. When freshwater inflow is larger than maximum flood-tide flows, net river velocities will be downstream during all of a tidal cycle. Otherwise, there will be twice-daily reversals of flow direction.

One important influence on estuarine flows which is not usually significant in ordinary river flow is the Coriolis Effect due to the earth's rotation. In the northern hemisphere, the Coriolis Effect tends to deflect a moving particle to the right of its direction of motion. On a flood tide, therefore, the water moving upstream tends to hug the left bank. (U.S. Geological Survey convention assigns right and left bank in the sense of facing downstream). On an ebb tide, the flow tends to hug the right bank. Because the net flow in an estuary is downstream, there is an overall tendency for flows to hug the right bank. With regard to salinities, however, the observed tendency is for salinities to always be higher on the left bank than on the right during both

flood and ebb tides. Presumably, this is because flood tides, which carry saline water upstream, tend to hug the left bank, causing higher salinities there; ebb tides, which carry fresher water downstream, tend to hug the right bank.

These observations have obvious value in locating water intakes for water supply or outfalls for waste water. All other factors being equal, the right bank would be the obvious choice for the location of freshwater intakes because water may be less saline (be of better quality) and for waste outfalls because flows on ebb tides would be greater (for better dilution and transport of wastes).

Salinity

At this point, the term salinity needs to be more precisely defined and discussed. Salinity refers to the degree of saltiness of water, or more specifically, the concentration of dissolved solids in water. The generally accepted formal definition of salinity was given by Forch and others (1902) who defined it as "the total amount of solid material in grams contained in one kilogram of seawater when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized." Even though this formal definition refers to salinity as an amount, in practice salinity is generally expressed as a concentration, in parts per thousand of sea water ($^0/_{00}$) or milligrams per liter of dissolved solids (1,000 mg/L is approximately equal to 1 part per thousand).

Average concentrations of the major constituents of seawater as determined by Jacobsen and Knudson (1940) are given below:

Constituent	Concentration (mg/L)
Chloride (Cl)	18,980
Sodium (Na)	10,556
Sulfate (SO4)	2,649
Magnesium (Mg)	1,272
Calcium (Ca)	400
Potassium (K)	380
Bicarbonate (HCO3)	140

These constituents account for 34,377 out of the total of 34,482 mg/L of dissolved solids in seawater. Although these values are the standard used in this report, it should be recognized that concentrations of constituents in seawater vary from time to time and place to place. For example, the total dissolved-solids concentration of 17 samples of seawater collected near Wrightsville Beach, North Carolina,

by the U.S. Geological Survey between 1963 and 1965, ranged from 31,900 to 35,900 mg/L. However, these variations do not differ appreciably from the average of 34,482 mg/L of dissolved solids and thus they are of minor importance in accounting for salinity variations in North Carolina estuaries. Even where the total salinity of seawaters varies, the relative concentrations of major ionic species remains constant--and the salinity of a given water may be approximately determined if the concentration of any one of the major constituents of the water is known. For example, if the chloride concentration of a given water is 10,000 mg/L, then the salinity is $\frac{10,000}{18,980} \times 34.5\ ^{0}/_{00} = 18.2\ ^{0}/_{00}$.

Determinations of individual chemical constituents, such as chloride, can be time-consuming or otherwise impractical in some situations. Salinity is often determined in the field by measurement of specific conductance of the water. The specific conductance, measured in micromhos (μmhos), is proportional to the dissolved-solids concentration of the water. Because the ratio of the concentration of a given major constituent dissolved in seawater to the total dissolved-solids concentration of seawater is almost constant, specific conductance may be used to estimate the concentration of any of the major constituents of sea water. Such a relation has been prepared for specific conductance versus chloride and dissolved solids (fig. 1.5).

Chloride is a particularly important constituent because it is often a limiting element in determining suitability of a water supply for public or industrial use. The National Academy of Sciences (1972) [1974] recommends an upper limit of 250 mg/L of chloride for drinking water, and water with 500 mg/L or more is unsuitable for a number of industrial uses. Thus, the 200 mg/L of chloride criterion used in this report (equivalent to a specific conductance of 800 μmhos in figure 1.5) to indicate the presence of saltwater is within the National Academy of Science's recommended upper limit for drinking water.

Estuarine Types

Mixing of freshwater and seawater takes place through turbulent mixing and molecular diffusion. The rates of mixing depend on channel geometry, the relative amounts of freshwater inflow and tidal flow, wind, and the differences in density between seawater and freshwater. (Seawater has a specific gravity of about 1.025 as compared to about 1.000 for freshwater.) Most mixing situations produce one of three "types" of salinity patterns--highly stratified, partially mixed, and well mixed. Estuaries are often classed according to which of these mixing patterns predominates. Among North Carolina estuaries, examples of each type can be found. It is worthwhile, therefore, to discuss the characteristics of each.

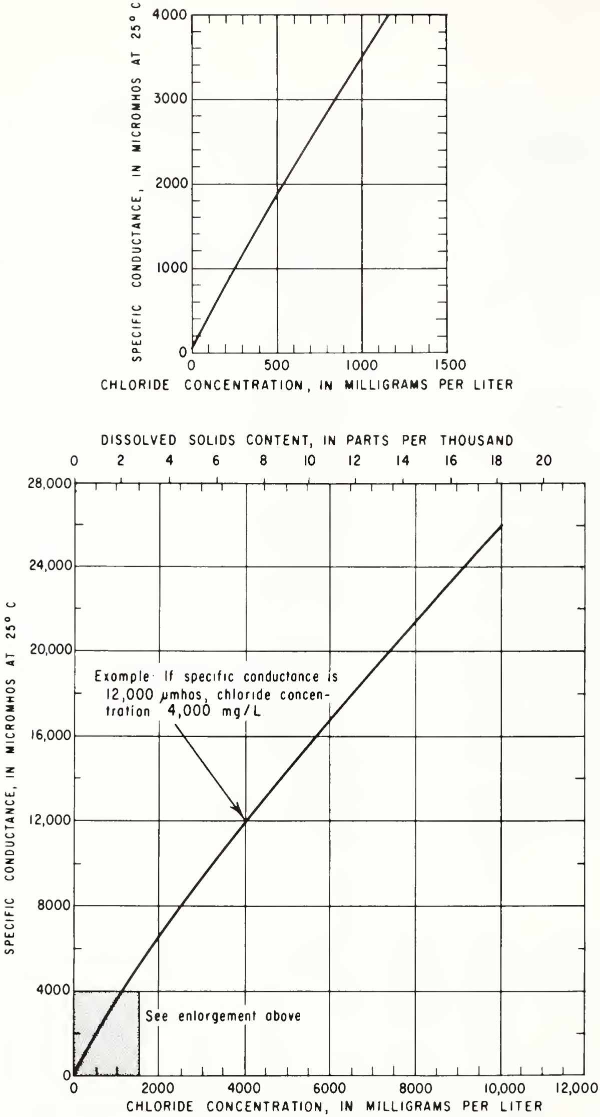


Figure 1.5.--Relation between specific conductance and chloride concentrations in North Carolina estuaries.

In a <u>highly stratified</u> estuary, the freshwater, being less dense, tends to ride over the top of the seawater (Fig. 1.6). Viscous shear forces along the boundary between the freshwater and seawater cause much turbulent mixing, making this a zone of rapid transition between freshwater and seawater. Turbulence patterns within this transition zone are such that the water has a net upward circulation and seawater becomes entrained with the freshwater moving downstream. This phenomenon of upward breaking waves has been discussed by, among others, Pritchard and Carter (1971) and Bowden (1967).

Thus, seawater directly below the transition zone retains its salinity, while freshwater above becomes more mixed with seawater as it moves further downstream. Finally, at some downstream point, the water flowing near the surface becomes indistinguishable from seawater. The rapid salinity change in the transition zone is evident from examination of section x-x' in figure 1.6B.

Net velocity under highly stratified conditions (fig. 1.6B) is downstream near the surface, is drastically less in the transition zone, is zero somewhat below the transition zone, then is upstream in direction at greater depths. If the velocities along this profile were integrated over a period of time, the resultant net flow would of course be downstream due to the energy gradient of the freshwater inflow. This energy gradient accounts for the net downstream flow in the upper levels of the river, while the net upstream flow near the channel bottom is from energy provided by gravitational convection. (Flows along the channel bottom due to gravitational convection are often referred to as density currents.) The saltwater wedge, which would otherwise move upstream to the limit of tidal influence due to density differences between freshwater and seawater, is constantly being eroded by contact and mixing with freshwater. This lost seawater is replaced by seawater moving upstream along the channel bottom. Thus, an equilibrium of the net position of the saltwater wedge may be maintained.

A highly stratified condition may exist in an estuary only when the freshwater inflow is large in relation to tidal flow. A rule of thumb given by Schubel (1971) is that, in order to have highly stratified conditions, the volume of freshwater entering an estuary during a half-tidal period (6.21 hours) should be at least as great as the volume of water entering during a flood-tide. In other words, the ratio of the freshwater volume to the flood-tide volume should be at least 1.0. This ratio is called the "mixing index." The reliability of the mixing index in predicting the degree of estuary stratification is influenced by channel geometry. As width increases or depth decreases, an estuary tends to become less stratified for a given mixing index.

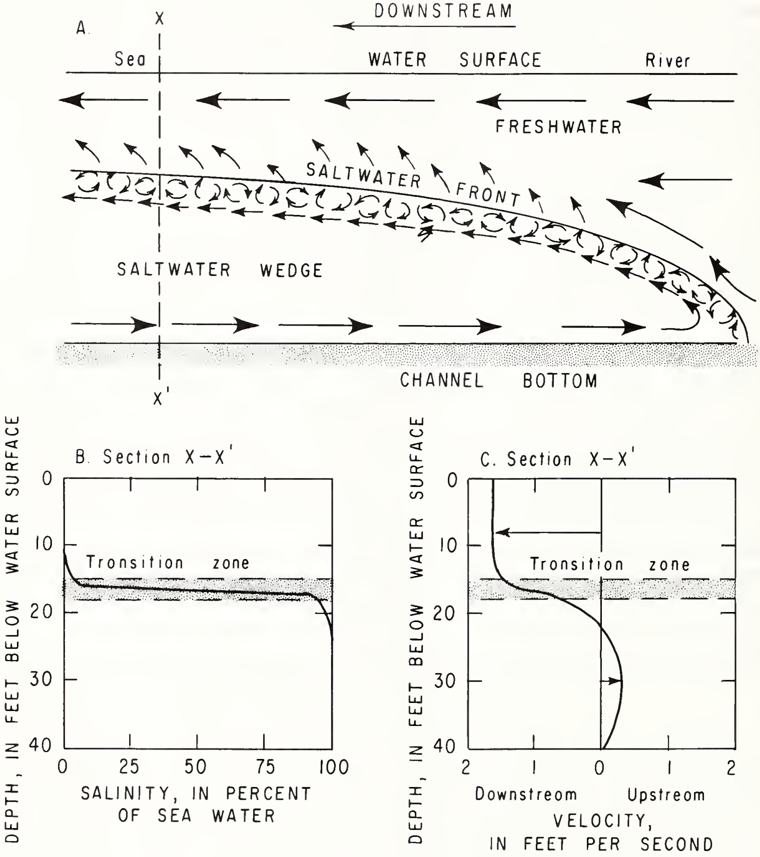


Figure 1.6.--A. Net circulation patterns in a highly stratified estuary. B. Salinity profile through section X - X'. C. Net velocity profile through section X - X'.

If the freshwater inflow becomes smaller in relation to the flood-tide volume (within a mixing-index range of about 0.05 to 1.0) then partially-mixed conditions may prevail, as sketched in figure 1.7A. In this situation flow reversals will probably occur throughout the depth of the estuary during at least part of each tidal cycle. (By contrast, flow along the surface at some point in a highly stratified estuary may be downstream at all times and flow near the channel bottom in the saltwater wedge may be upstream at all times.) Under partially-mixed conditions tidal flow dominates and the added turbulence from this source provides the means for eradicating the saltwater wedge. Not only does seawater mix upward into what was the freshwater zone, but freshwater mixes downward into what under highly stratified conditions was a zone of seawater. The sharp interface which separated the freshwater from the seawater in the highly stratified estuary is replaced by a much broader zone of moderate change in salinity. The saltwater front is shown in profile in figure 1.7A, and other lines of equal chloride concentration would have similar attitudes. The net changes in chloride concentration with depth through section Y-Y' (fig. 1.7B) are gradual. The lack of a sharp interface between fresh and saltwater is apparent, but some degree of stratification remains.

The variations in net velocity with depth are not obvious from the circulation arrows shown on figure 1.7A, which show only that turbulent mixing is present throughout a wide region. However, a definite pattern does exist, as shown in figure 1.7C. As in a highly stratified estuary, net velocities in the upper layers of the channel are downstream and net velocities in the lower layers are upstream. However, instantaneous flow at a particular point in many partially-mixed estuaries may be upstream or downstream at a particular moment at any depth.

An unusual feature of flow in a partially-mixed estuary is that the rates of flow in both the upper and lower layers may be an order of magnitude higher than river flow. For example, if F is the freshwater inflow, the upper-layer net seaward flow may be 10F. Since the estuary as a whole is neither filling nor emptying, then 9F must be brought up the estuary from the sea in the lower layers. Examples of this phenomenon have been verified for the James River in Virginia and the Chesapeake Bay (Pritchard and Carter, 1971, p. IV 7).

The third major type of estuary is termed well-mixed. Figure 1.8A shows the profile of the saltwater front in a well-mixed estuary. It is nearly vertical, which indicates that mixing forces are greater than in a partially-mixed situation. Schubel (1971) indicates that the upper limit for the mixing index is probably about 0.05 for well-mixed conditions to exist. In this situation, freshwater inflow is very small in relation to tidal flow. Because salinities are nearly homogeneous vertically, density currents are negligible. Thus, velocities are unidirectional from top to bottom at a given time in a given profile, as shown in figure 1.8C. With regard to salinity, although there may be

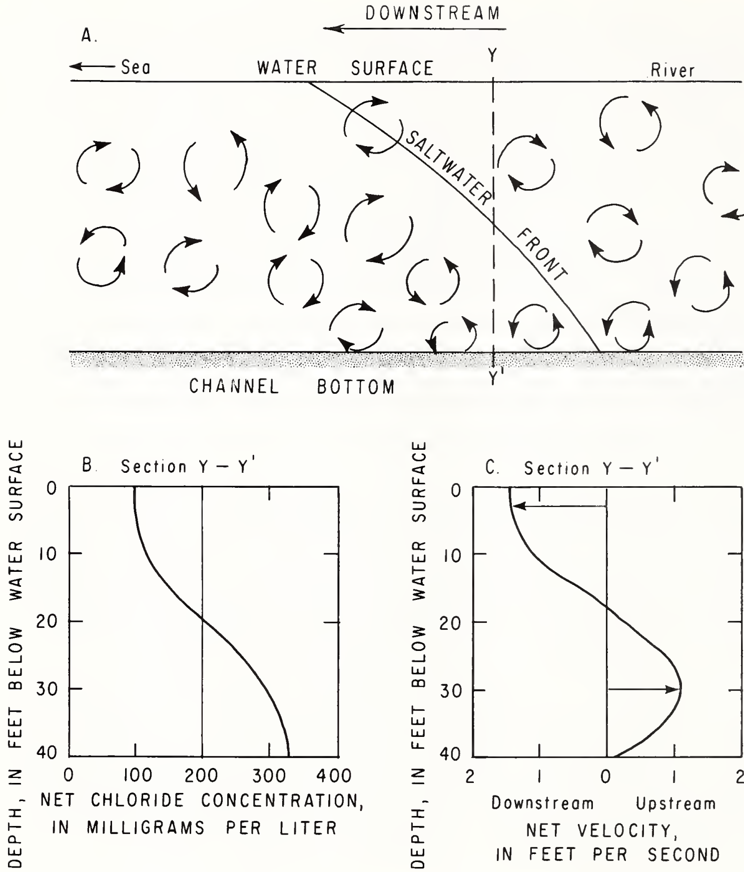


Figure 1.7.--A. Net circulation patterns in a partially mixed estuary. B. Chloride concentration profile through section Y - Y'. C. Net velocity profile through section Y - Y'.

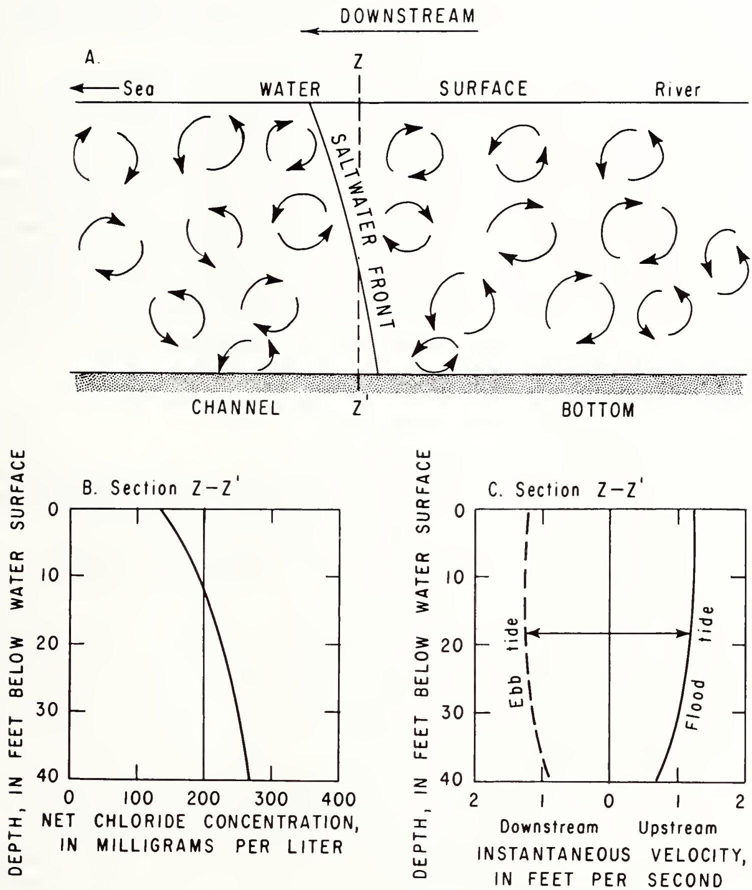


Figure 1.8.--*A. Net circulation patterns in a well-mixed estuary. B. Chloride concentration profile through section Z - Z'. C. Velocity profiles through section Z - Z'.*

some slight changes from top to bottom in a well-mixed estuary (figure 1.8B), the changes are uniform, without the zone of more rapid change characteristic of partially-mixed and highly stratified estuaries (fig. 1.6B and 1.7B).

The above discussions provide a framework for understanding salinity changes as related to circulation patterns in estuaries. Although three types of estuaries were discussed, it should be recognized that there is an almost continuous spectrum of salinity and circulation patterns and that there are gradual transitions between the three types. In fact, a given estuary may be highly stratified in the spring during periods of high freshwater inflow, partially mixed in the early summer, and well mixed in the fall when freshwater inflow is minimum. Within the same estuary, for a given mixing index, the mixing type may change as the saltwater front moves into an area of changing channel geometry. The general rule with respect to channel geometry is that an estuary tends to shift from a highly stratified to a well-mixed condition with increasing width and decreasing depth (Schubel, 1971, p. IV-14).

Sediment

The mechanics of transport and deposition of sediment in an estuary are far more complex than in ordinary streams. Yet, because of the impact of sediment deposition on aquatic life and on navigation and because large sums of money are spent in dredging and maintaining navigation channels and boat facilities, it is important to develop a clear understanding of the principles of estuarine sedimentation.

Sediment, whether moving in a free-flowing stream or in an estuary, has two components--suspended sediment and bed load. Suspended sediment comprise particles that are held in suspension by the upward components of turbulent currents and finer particles held in colloidal suspension. Bed load consists of material too heavy to be held in suspension but which nevertheless moves by sliding, rolling or skipping along the bed of a stream or estuary. In a free-flowing stream, however, net flow (and, therefore, sediment discharge) is always downstream and usually changes in magnitude slowly, whereas in an estuary the tide-affected flow (and therefore sediment discharge) is almost always changing rapidly in magnitude and direction. Changes in chemical quality along streams are usually small and have negligible effect on sediment concentrations, whereas quite dramatic changes in chemical quality occur within estuaries and these may profoundly influence sediment transport characteristics.

In many estuaries, a characteristic zone of high concentrations of suspended sediment and high turbidity begins near the saltwater front and, in some estuaries, continues downstream for miles. This zone has been discussed by, among others, Ippen (1966) and Schubel (1971).

Upstream from this zone, in the freshwater portion of the estuary, concentrations are less; downstream from this zone, in the ocean, concentrations are also less. The probable explanation for this zone is that such estuaries act as sediment traps. This may be better understood by referring back to the net circulation patterns on figure 1.6C for a highly stratified estuary. Imagine suspended sediment being carried out to sea in the top layers of freshwater during ebb flow. As the time of slack water approaches where the estuary widens towards the mouth or as the freshwater spreads out over the bays and adjacent ocean, velocities decrease, thus allowing heavier sediment particles to settle. As they settle, they are entrained in water moving upstream along the channel bottom. At the upstream end of the saline water zone, flow circulates upward and downstream, and sediment particles may again be entrained upward and flow towards the sea in the upper freshwater layers. Again, the particles may settle as velocities decrease, and thus a sediment particle may be caught in a loop pattern several times.

This sediment-trap phenomenon is found to some extent in highly stratified situations, but is even more pronounced in partially-mixed estuaries where net upstream velocities near the channel bottom and net downstream velocities near the surface are much greater than in highly stratified estuaries. This phenomenon is probably not found to any significant extent in well-mixed estuaries, where there is no significant net upstream flow along the channel bottom.

The sediment trap zones in estuaries are, naturally enough, zones of high sediment deposition. Most of the deposited sediment in these zones is of clay or silt size. The particles tend to settle to the channel bottom wherever or whenever instantaneous or net velocities suddenly decrease or approach zero. The tip of a saltwater wedge is one area of rapid deposition because net velocity is zero in that vicinity. Other potential areas of deposition are where tributaries enter a slow-moving main channel, in bays, and in boat slips.

Another potential factor that may account for some sedimentation in the sediment trap zone is flocculation and subsequent deposition of clay-sized particles in the water. This process depends on the presence of electrolytes, such as sodium chloride, which neutralize the electronegative characteristics typically associated with sediment particles. Salt water is an electrolyte, and the settling of fine-grained particles is indeed observed in the saline water zone. However an additional or alternative binding mechanism brought about by filter feeding organisms has been advanced by Schubel (1971). He describes the results of an extensive size-analysis study of particles in suspension at all depths in Chesapeake Bay and the Susquehanna River. He reports on p. VII-20:

> "Many composite particles were observed, particularly in the lower layer, but careful microscopic examination showed that most were agglomerates weakly bound by organic matter and mucus and

probably produced by filter-feeding zooplankton. Preliminary experiments have indicated that suspension-feeding zooplankton probably play a major role in the agglomeration of fine particles in the water column, and in the subsequent deposition of those particles. The large population of filter-feeding zooplankton present in the Bay probably filter a volume of water equivalent to that of the entire estuary at least every few weeks, and perhaps every few days."

Previous to this statement Schubel stated that his evaluation techniques failed to produce any evidence of flocculation. In view of this, it might be safer to refer to these composite particles as agglomerates rather than flocculates. An agglomerate is a more general term meaning a composite particle composed of two or more individual particles held together by any relatively weak cohesive force. A flocculate is an agglomerate bounded by electrostatic forces.

Potential sources of silt and clay-sized sediment deposited in a sediment-trap zone are many. Studies on many United States estuaries have shown that sediment from upland discharge is inadequate in most cases to account for the shoaling rates that are observed in river channels and harbors. Ippen (1966, p. 654) lists other sources of shoaling material as follows:

"a) marsh areas adjacent to the estuary with runoff draining into the tidewater,

b) materials in larger estuaries being eroded from the shores by wave action and moving by density currents into the deeper portions,

c) materials being displaced by dredging and propeller wash and moved by density or tidal currents,

d) organic materials as a result of the biological cycles of estuarine plant and animal environment,

e) industrial and human wastes discharged into the estuary,

f) windborne sediment."

In addition to these sources mentioned by Ippen, sediment resuspended from the channel bottom and later redeposited in shoaling areas may also be an important factor in high local shoaling rates in some estuaries. In some cases, the open ocean adjacent to an estuary may also be a significant source of sediment.

Regarding sediment deposition, and attempts to improve existing shoaling characteristics, Ippen (1966, p. 650) makes the following points:

"a) sediments settling to the bottom zone in an estuary will on the average be transported upstream and not downstream,

b) sediments will accumulate near the ends of the saltwater intrusion zone and form shoals. Shoals will also form where the net bottom velocity is zero due to local disturbances of the regime such as by tributary channels,

c) the intensity of shoaling will be most extreme near the end of the intrusion for stratified estuaries and will be more dispersed in the well mixed estuary.

Therefore, with regard to human interference in existing estuary patterns, the following general rules may be derived:

a) the major portion of sediments introduced from whatever source into an estuary during normal conditions will be retained therein, and if transportable by the existing currents will be deposited near the ends of the salinity intrusion, or at locations of zero net bottom velocity,

b) any measure contributing to a shift of the regime towards stratification will cause increased shoaling. Such measures may be: structures to reduce the tidal flow and prism, diversion of additional freshwater into the estuary, deepening and narrowing the channel,

c) dredging of channels should be accompanied by permanent removal of the sediments from the estuary. Dumping downstream is highly suspect and almost always useless. Agitation dredging falls into the same category, if permanent removal is desired."

Although the principles discussed in this section are useful in understanding general aspects of estuarine sedimentation, the actual movement and deposition patterns of sediment in real estuaries are usually extremely complicated in detail, and may require hydraulic model studies to adequately define. Model studies of this kind are lacking for most sounds and estuaries in North Carolina. Nevertheless, some information about sedimentation in North Carolina sounds and estuaries is given in later sections of this report.

Effects of Winds and Hurricanes

Most estuaries are thought of as freshwater inflow dominated, tide-dominated, or some combination of both. However, several major estuaries in North Carolina fall into a less common category--wind-dominated.

To understand how these wind-dominated conditions exist, first consider that the Outer Banks greatly weaken ocean tides in Pamlico and Albemarle Sounds and their tributaries. For example, the mean tide range in the ocean off Cape Hatteras is about 3.6 feet, according to the National Ocean Survey, while the range within Pamlico and Albemarle Sounds is less than half a foot. Consider also that the channels of many estuaries west of the Outer Banks are very large for the amount of water they carry and that, consequently, velocities due to freshwater inflow into them are often very low. In this situation of weak currents from both tides and fresh-water inflow, wind-generated currents take on a relatively more important role. In addition, the funnel effect of wind-generated currents flowing into estuaries from Albemarle and Pamlico Sounds results in much stronger wind-generated currents in those estuaries than would otherwise occur. This combination of circumstances results in wind playing a much more prominent role in circulation and mixing patterns than would otherwise be the case.

The physics of water movement in response to winds is extremely complex. It is sufficient for our purposes to consider that, owing to friction between moving air and the water surface, a certain amount of water will be "pushed" in the direction toward which the wind is blowing. The amount of water moved depends upon several factors, the most important of which are the velocity of the wind, the continuous distance along the water-surface over which the wind is effective (called the fetch) and the depth of the water. Movement of water by wind becomes important when water levels adjacent to shore lines are adversely affected. Obviously, on-shore winds cause water to pile up along the shore, and offshore winds cause a lowering of water levels.

The interior shore lines of North Carolina have a complex configuration, and it is difficult to predict the effects of a given wind on water levels at a particular location. However, with certain modifications, the following equation (Bretschneider, 1966, p. 240) may be applied with useful accuracy to some estuaries and sounds of North Carolina for predicting wind setup (change in water level):

$$S = h\left[\sqrt{\frac{2kX}{gh^2}U^2 + n} - n\right] \qquad (1.1)$$

where: S = wind setup, or change in water level,

h = average depth,

k = constant empirically evaluated at 3.3×10^{-6},

X = effective length of water surface over which wind is acting, or fetch,

U = wind speed,

n = constant, which is unity in a rigorous solution of the deriving equation. (Where calibration data are available for a particular location, n can be empirically changed to obtain more precise estimates of S.), and

g = acceleration due to gravity

To use equation 1.1 to estimate the change in water level caused by winds at some point along the shoreline of the sounds, it is necessary to determine the component of wind that will be effective in producing the greatest change in water level at a point of interest. The effective component will usually be the component acting along the longest continuous line of fetch to the point where the increase in water level is to be calculated. For a given wind the component is calculated from the angle of departure of the actual wind direction from the effective line of fetch. By simple trigonometry the effective wind speed is:

$$U_e = U_a \cos \alpha \tag{1.2}$$

where: U_e = effective wind speed,

U_a = actual wind speed, and

α = angle of departure of wind direction from the effective line of fetch.

As an example of the use of equations (1.1) and (2.2), suppose the wind is blowing from the east at 30 mi/h (44 ft/s). The angle of departure of wind direction from a line perpendicular to the coast is 20°. The average depth along the fetch is 40 ft. The length of the fetch over which the wind is acting (distance perpendicular to the coast) is 50 miles (264,000 ft). Solving equation (1.2) first:

$$U_e = (44 \text{ ft/s}) (\cos 20°) = (44 \text{ ft/s}) (.9397) = 41.3 \text{ ft/s}$$

Solving equation (1.1), for eventual wind setup, S,

$$S = 40\left[\sqrt{\frac{2(3.3\text{x}10^{-6})(264{,}000)}{32.2\ (40)^2} \text{ x } \frac{(41.3)^2}{1} + 1} \quad -1\right]$$

$$S = 40\left[1.028439-1\right] = 40\ \left[.028439\right] = 1.13 \text{ ft}$$

In practice, a curve is plotted from equation (1.1) showing S versus U_e. Where possible, actual observations of S and U are used to adjust the constants in equation (1.1) and a final equation is developed which most accurately defines conditions at a particular location. A "wind compass" is developed on which the various angles of departure in equation (1.2) are plotted as adjustment coefficients. To determine setup for a given wind at a given location, it is only necessary to use the wind compass to determine the adjustment coefficient, multiply the actual wind speed by this coefficient, and consult the "S versus U_e" curve for that location.

Like most coastal areas, North Carolina's shorelines are affected by a full range of winds, from gentle breezes caused by temperature differentials between land and ocean to violent winds associated with major storm systems. Predictable diurnal and seasonal shifts in wind direction cause daily and seasonal shifts in tide heights and currents. However, the most dramatic wind effects are those associated with hurricanes, which seasonally threaten the eastern parts of the State. Since 1870, approximately one hundred storms of hurricane force have to some degree affected eastern North Carolina. One of the most spectacular and destructive was Hurricane Hazel which, on October 14, 1954, caused an estimated 100 million dollars worth of wind and water damage throughout the eastern one-third of the State and forced saltwater further upstream into the estuaries than ever recorded before or since.

The effects of hurricanes on water levels along the coast are extremely complex. As illustrated on figure 1.9., hurricane winds in the Northern Hemisphere circulate in a counter-clockwise pattern around an eye, usually from 50 to 75 miles in diameter, within which winds are calm to very light. Depending upon the position of this eye relative to a particular location, winds associated with the storm may come from any direction. Should a part of the eye pass over the location, two periods of high wind velocity separated by a period of calm will be observed. Wind directions of the two high-wind periods may be out of phase with one another by nearly 180°. It is also worthy of note that effective wind speeds to the right side of these storms (with regard to the general direction of motion) are greater than those on the left side. In the North Carolina area, hurricane systems usually move at speeds of 5 to 40 miles per hour, and this forward motion is additive to wind speed due to the counterclockwise motion of the circulation system.

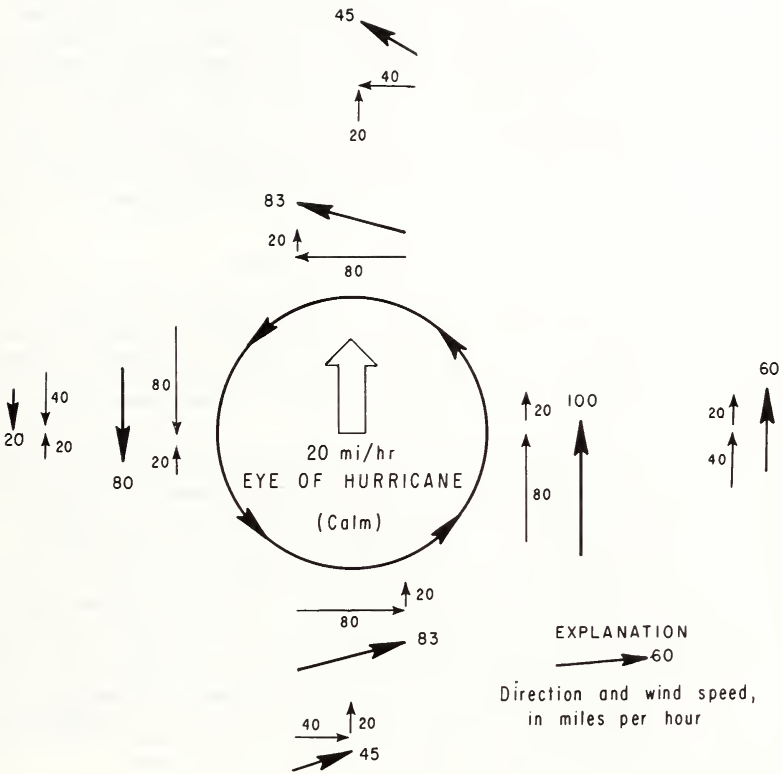


Figure 1.9.--The effect of forward motion of a hurricane on wind velocities in each quadrant.

The overall effect of this complex pattern of hurricane winds is that resulting water-level changes are even more complex. At a given point on the shore, water levels may be either raised or lowered, or first raised then lowered, or first lowered then raised. The need to protect against hurricane damage has led to the development of sophisticated mathematical models to predict hurricane surge. Although a complete discussion of these models is beyond the scope of this report, the reader is referred to Amein and Airan (1976) for a presentation of a mathematical model of circulation and hurricane surge in Pamlico Sound. Later chapters of this report indicate the susceptibility of many of North Carolina's coastal areas to hurricane-induced flooding.

The Salt-Marsh Environment

Thus far, we have been concerned only with general principles of hydrology which will be applied in describing the major sounds and estuaries of North Carolina in following sections of the report. However, the salt-marsh environment, a rather unique and important type of estuarine environment, deserves some general discussion here, also.

Much of the coastal fringe areas of North Carolina's sounds and estuaries may be classified as a salt-marsh type of environment. These areas are ecologically very important for several reasons. First, they serve as nurseries for a variety of animals that are harvested in important commercial and sport fisheries; these include shrimp, crab, scallop and many fish species. Secondly, salt marshes are very productive natural areas upon which many animals depend for food. An estimated 65 percent of the total commercial fisheries catch in coastal waters of the eastern United States is made up of species that depend directly in one way or another on salt marshes and estuaries during some phase of their life cycles (McHugh, 1966). The 1973 dockside value of the North Carolina commercial fishery harvest was about $16 million, and the value is increasing every year (Thayer, 1975, p. 62). In addition, about $100 million is spent annually by North Carolina and out-of-state residents for sport fishing in coastal waters of the State.

As of 1962, North Carolina contained about 58,400 acres of regularly flooded salt marshes and about 100,450 acres of irregularly flooded salt marshes (Wilson, 1962). The most abundant plants in these salt marshes are saltwater cordgrass and needlerush, with grasswort and salt meadow cordgrass occurring in lesser densities (Frankenberg, 1975, p.55). The primary productivity (plant production) of the salt-marsh environment is phenomenal--twenty times as productive as the open ocean and one to two orders of magnitude higher than most other ecosystems--they are rivaled in production only by tropical rain forests and highly cultivated land. Table 1.2 gives comparative production rates for the North Carolina salt marshes and various cultivated crops. Plant matter from these lush salt marsh areas is consumed either directly by some

marine animals (such as shrimp, mullet, and zooplankton) or indirectly by others which eat the direct consumers.

Table 1.2.--Primary production rates of various ecosystems. (Adapted from Odum, 1959, and Keefe, 1972.)

System	Net primary production rate, in pounds of plant material per acre per year
Hay - U.S. Average	3,738
Highest (California)	8,366
Wheat - World Average	3,497
Highest (Netherlands)	11,867
Corn - World Average	6,102
Highest (U.S.)	11,442
Rice - World Average	5,686
Highest (Japan)	13,597
North Carolina Salt Marshes	
Saltwater Cordgrass (*Spartina alterniflora*)	
regularly flooded	11,570
irregularly flooded	5,429
Needlerush (*Juncus roemarianus*)	
regularly flooded	9,834
irregularly flooded	6,034
Saltmeadow Grass (*Spartina patens*)	
regularly flooded	11,534
irregularly flooded	8,837

The salt-marsh environment, important as it is in the life cycles of many marine (and freshwater) organisms, is a fragile one--subject to adverse effects from changes, not only from a wide variety of natural phenomena, but also from encroachment by man. Pollution, landfill and dredging, building, drainage of marshes, and alteration of freshwater flow regimes are some of the activities of man that either destroy or have adverse effects on the saltmarsh environment and marine organisms which are directly or indirectly dependent on it. Tihansky and Meade (1974) estimate that, nationally, we are losing for fishery production about 1 percent per year of our total estuarine environment. The annual percentage lost from salt-marsh areas may be even higher.

Many of the problems associated with maintaining a viable salt-marsh environment are related to changes in hydrology, either natural or man-induced. Heath (1975) reports on the hydrologic impact of agricultural developments in the Albemarle-Pamlico region, many of which affect the salt-marsh areas. He points out that drainage canals built in conjunction with large-scale corporate farming developments remove fresh-water runoff to the coast more quickly than the previous natural system. During periods of heavy runoff through drainage canals, salinities may be reduced in salt marsh areas to the point where young shrimp and other marine fishes sensitive to low salinities are forced out of the protective food-rich muck of the salt marshes into more-saline unprotective sandy-bottom areas where conditions are much less favorable for their survival.

High sediment loads are another problem associated with high flows and also with construction activities. Clay-sized particles, particularly, may harm bottom-dwelling and filter-feeding organisms by clogging their feeding apparatus and hampering burrowing activities.

Many salt-marsh areas are affected to some degree by pollution from agricultural areas. This pollution may be of several types--high levels of total coliform bacteria, fecal coliform bacteria from human and animal wastes, pesticides, and nitrogen and phosphorous (nutrients which may promote destructive algal blooms).

The Geological Survey is conducting several studies in cooperation with the North Carolina Department of Natural Resources and Community Development which bear on these issues. One, a study of the effects of land clearing and drainage canals on the hydrology of the Albemarle-Pamlico region, deals in part with effects on salt-marsh areas. Another seeks to determine drainage areas of streams throughout North Carolina - including the drainage areas of many small coastal streams which are at present undetermined.

CHAPTER 2

HYDROLOGY OF THE CAPE FEAR RIVER ESTUARINE SYSTEM

Together, the lower Cape Fear and Northeast Cape Fear Rivers comprise what we will term the Cape Fear River estuarine system. (See plate 1.) Actually, the Northeast Cape Fear River basin (drainage area - 1,740 mi^2) is a subbasin of the Cape Fear River basin (total drainage area - 9,140 mi^2) and the the Northeast Cape Fear River estuary may be thought of as a branch of the Cape Fear River estuary. Nevertheless, for ease of analysis the Northeast Cape Fear River estuary will be discussed separately.

The Cape Fear River and the Northeast Cape Fear River estuaries are the only major estuaries in North Carolina having a relatively free and direct access to the ocean, which results in significant tides and tide-affected flow within them. In the Cape Fear River estuary, tides extend up to Lock 1, about 65 miles upstream from the mouth near Southport. As shown in plate 1, the mouth is at a river cross-section extending from Fort Caswell east to the western tip of Smith Island. Tide effects in the Northeast Cape Fear River estuary extend to about 48 miles from its mouth at Wilmington, which in turn is located about 28 miles upstream from the mouth of the Cape Fear River estuary.

The lower reaches of the Cape Fear River and Northeast Cape Fear River estuaries are subject to saltwater intrusion, sometimes rendering the water unsuitable for some uses. Plate 1 shows the approximate extent of saltwater intrusion in both estuaries, that is, the furthest upstream advance of water containing 200 mg/L of chloride ever known and the furthest upstream advance that has a 50 percent chance of being equaled or exceeded in any year.

Rapid industrial growth has taken place along the banks of the two estuaries in recent years, and a number of industries use the water from them as process water and discharge industrial wastewater into them.

The Cape Fear River and Northeast Cape Fear River estuaries are important navigable waters, and navigation channels are maintained to various depths by the U.S. Army Corps of Engineers. The channel dimensions maintained for navigation will be discussed in more detail in following sections of this report.

The summaries of the hydrology of the Cape Fear River and Northeast Cape Fear River estuaries are based on data and other information from various sources, primarily the Geological Survey. Plate 1 shows the location of key flow and water-quality stations operated in the Cape Fear River basin by the Geological Survey. These stations include the Cape Fear River at Phoenix (sta. no. 02107570), where the Geological

Survey generated records of volumes of water flowing upstream and downstream during each tidal phase for the period April 1966 through March 1969. Data from these stations are published annually in the U.S Geological Survey water-data report series for North Carolina. Wilder and Slack (1971a and 1971b) summarized data on chemical quality of streams in North Carolina from 1943 through 1967. Wilder and Hubbard (1968) reported on saltwater encroachment in the Cape Fear River estuary; Hubbard and Stamper (1972) reported on the movement and dispersion of soluble pollutants in the Northeast Cape Fear River estuary; the U.S. Corps of Engineers (1976) discussed sedimentation and related aspects of hydrology in the lower Cape Fear River estuary. These and other sources of information are acknowledged in the text where appropriate.

The Cape Fear River Estuary

The Haw and Deep Rivers, two major tributaries of the Cape Fear River, head in the Piedmont Province and flow southeast, joining at Moncure, to form the Cape Fear River (plate 1). From Moncure, the Cape Fear River flows southeast through the Coastal Plain to its mouth near Southport. The Cape Fear River drains a larger part of North Carolina than any other river; the drainage area at the mouth is 9,140 mi^2, all of which is in North Carolina. Of this, the Deep River accounts for 1,422 mi^2 and the Haw River accounts for 1,705 mi^2. Other major tributaries include the Black River (1,563 mi^2) and the Northeast Cape Fear River (1,740 mi^2).

Prior to the construction of Lock 1 about 37 miles upstream from Wilmington, river stage was affected by ocean tides possibly as far as 50 to 75 miles upstream from Wilmington. The construction of Lock 1 eliminated the effect of ocean tides above this point and this lock, therefore, marks the upstream limit of tide effect at the present time. The total length of the estuary from its mouth to Lock 1 is about 65 miles.

The lower part of the estuary, beginning about three miles below Wilmington, averages about a mile in width and contains numerous scattered islands and a few tidal flats. It resembles an elongated bay only a few feet deep except along the ship channel which has been dredged and maintained in this reach to depths of 32-40 feet and widths of 300-500 feet. By comparison, the channel above Wilmington is narrow, with depths ranging from 20 to 60 feet. Tidal currents in the upper reach, particularly near the lower end, are strong and velocities may exceed 3 ft/s.

Flow

Flow in the Cape Fear River estuary is strongly tide-affected. Except during periods of high freshwater inflow, regular reversals of flow occur with each tide. During periods of higher-than-average freshwater inflow, outflow at some or all locations in the estuary may be high enough to overwhelm incoming flood tides, resulting in a period when no flow reversal occurs. Because the freshwater inflow is such an important component of flow in the estuary, it will be discussed at length before further considering tide-affected flow.

Freshwater inflow.--The average discharge at the mouth of the Cape Fear River estuary is about 11,000 ft^3/s. Because of the difficulty of accurately measuring flows in the estuary portion of the river, values for discharges were arrived at by summation of flows for gaged areas within the basin and estimates of flows for ungaged areas.

The major part of the freshwater inflow is measured at the stream-gaging stations shown on plate 1. The stations closest to the estuary gage the runoff from 6,660 mi^2 or 72 percent of the total 9,140 mi^2 of drainage area above the mouth of the estuary. The three stations of greatest importance are the most downstream stations on the Cape Fear, Black, and Northeast Cape Fear Rivers. The runoff from 6,500 mi^2 of the Piedmont and the inner part of the Coastal Plain is measured at the three stations listed below:

Number	Name	Drainage area
02105769	Cape Fear River at Lock 1 near Kelly	5,220 mi^2
02106500	Black River near Tomahawk	680 mi^2
02108000	Northeast Cape Fear River near Chinquapin	600 mi^2

These stations will be referred to as Lock 1, Tomahawk, and Chinquapin, individually, and collectively as index gages.

The largest ungaged areas are in the lower part of the Coastal Plain, the area adjacent to the estuary itself. Most of the runoff from the total area of 2,640 mi^2 below the index stations is ungaged. However, a relationship between the runoff from this ungaged area and the combined runoff at the Tomahawk and Chinquapin stations was established by obtaining periodic base flow measurements at sites in the ungaged areas and relating these on a per square mile basis to concurrent discharges at Tomahawk and Chinquapin (fig. 2.1). These two stations were used in the relation because they drain only areas in the Coastal Plain. The net outflow from the estuary is the sum of discharges for the three index stations plus that contributed by the ungaged area, which can be estimated from figure 2.1.

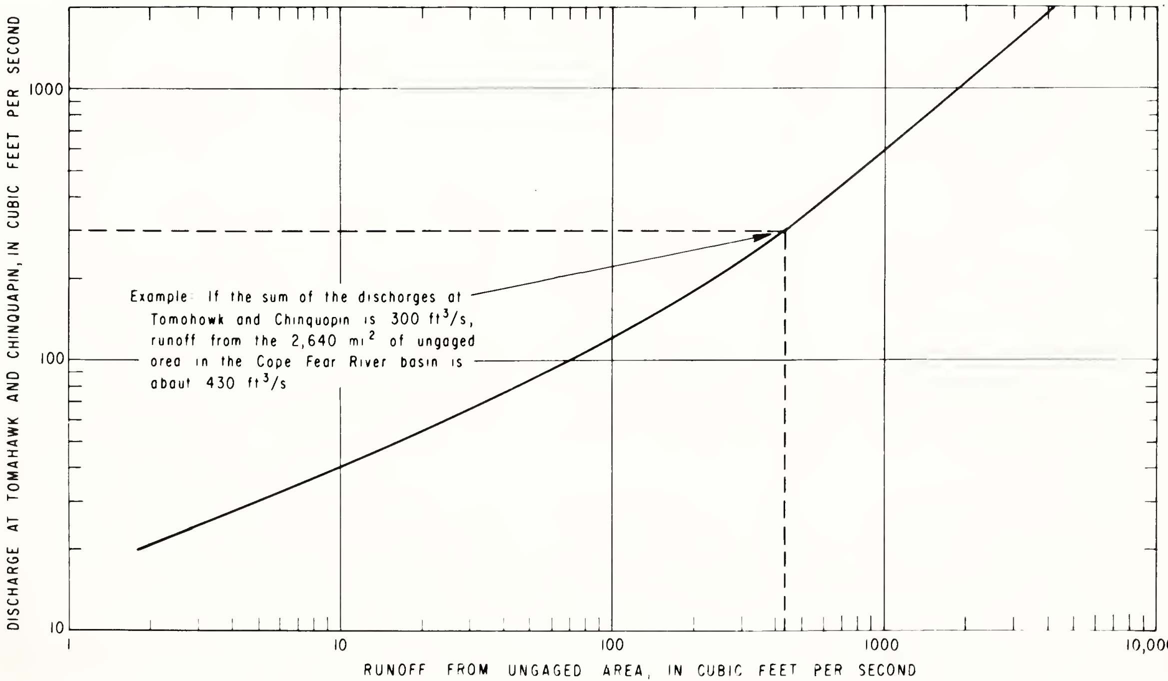


Figure 2.1.--Concurrent discharge relation for estimating runoff from the ungaged drainage area between the index stations and the mouth of the Cape Fear River estuary. Modified from Wilder and Hubbard, 1968.

Because steady-flow conditions rarely occur throughout the Cape Fear River basin, lag-time corrections must be applied to streamflow records at the various gages in order to arrive at an estimate of freshwater outflow from the estuary at a given time. Lag times, computed from theories of wave celerity and rounded to the nearest whole day, are 2 days from Tomahawk to the mouth of the Black River and 3 days from Chinquapin to the mouth of the Northeast Cape Fear River.

Combining all flow components, the following empirical equation was developed for estimating fresh-water outflow (Q_t) from the estuary,

$$Q_t = Q_1 + Q_2 + Q_3 + Q_4 \tag{2.1}$$

where Q_t = total outflow from the estuary,

Q_1 = discharge at Lock 1 at day of Q_t,

Q_2 = discharge at Tomahawk two days prior to Q_t,

Q_3 = discharge at Chinquapin three days prior to Q_t, and

Q_4 = runoff obtained from figure 2.1 using $Q_2 + Q_3$.

Equation 2.1 was used to calculate average 7-day outflows. The 7-day period was chosen because it was long enough to dampen the effects of minor, localized variations in the pattern of basin runoff and short enough to be a sensitive parameter for relating inflow to the position of the saltwater front.

Insofar as water supply, sewage dilution, and saltwater encroachment in the Cape Fear River are concerned, the most critical flow periods are usually those of sustained low flow. Figure 2.2 shows the average recurrence interval, in years, at which various average 7-day minimum flows may be expected to occur. These values were generated by combining estimated annual 7-day minimum flows for the various flow components of equation 2.1. It is interesting to note that if the B. Everett Jordan Reservoir (plate 1) is filled and if releases from it are controlled according to the proposed operating schedule, then the minimum flow of the Cape Fear River at Lillington is expected to be no less than 600 ft^3/s. Based on this, the minimum discharge at the mouth, near Southport, might be about 800 ft^3/s, compared to an estimated 300 ft^3/s at present for the 7-day, 100-year minimum net discharge near Southport.

Tide-affected flow.--Flow of the Cape Fear River estuary is strongly influenced by ocean tides. The U.S. Geological Survey operated a tidal discharge gaging station near Phoenix (sta. no. 02107570) from April 1966 through March 1969. (See fig. 2.3.) The purpose of this station was to develop information on tide-affected flows for the estuary which could prove useful, for example, in better understanding the movement and dispersion characteristics of water substances discharged

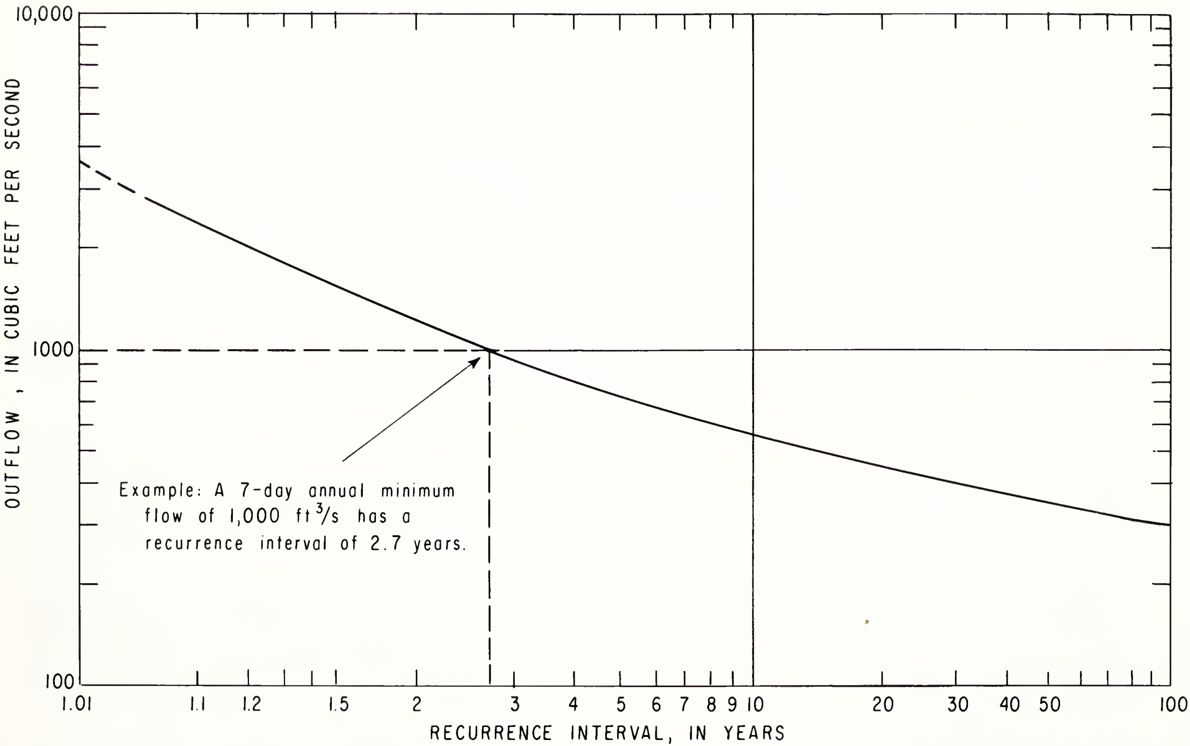


Figure 2.2.--Magnitude and frequency of annual minimum 7-day average net flow of the Cape Fear River estuary at the mouth, near Southport.

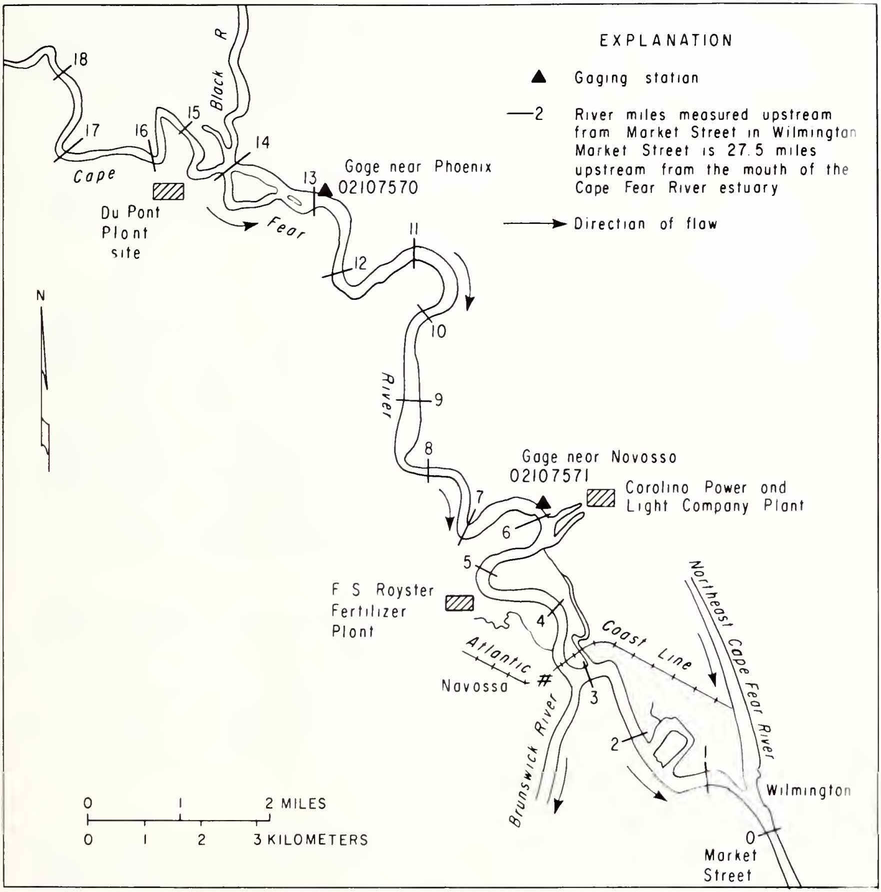


Figure 2.3.--Cape Fear River estuary upstream from Wilmington.

to the river or in better understanding the mechanics of sediment transport and deposition. Volumes of water flowing upstream and downstream on each tidal phase were published in the annual data reports of the U.S. Geological Survey. Calibration measurements were made over full or nearly full tidal cycles on three occasions--May 11 and 12, 1966, March 8, 1967, and July 27, 1967.

Partial results of the March 8, 1967 series of measurements are shown in figure 2.4. This series of measurements was made under fairly typical tide-affected flow conditions and provided, with other information, a means to calculate the minimum freshwater inflow required to prevent flow reversals in the vicinity of Phoenix.

Figure 2.4 shows that the maximum measured discharge on March 8, 1967, was 15,400 ft^3/s downstream at 1500 hours on ebb tide. By contrast, the maximum discharge on flood tide was 6,690 ft^3/s upstream at 1915 hours. The average flow over the tidal cycle was 6,240 ft^3/s downstream at the Phoenix gage. This value appears reasonable compared with the estimated freshwater flow at Phoenix for March 8 of about 6,500 ft^3/s. From this information, it appears that little or no upstream flow should occur near Phoenix whenever the freshwater inflow exceeds about 13,000 ft^3/s. Downstream from Phoenix, the tidal component of flow would be larger and a correspondingly larger freshwater inflow would be required to prevent flow reversal. Upstream, the tidal component would be less and the freshwater inflow required to prevent reversal would be less also.

Two other facts from figure 2.4 are worth noting. First, times of high and low tides do not occur simultaneously with times of high and low slack water. Rather, slack water occurs from one-half to one-and-a-half hours later than high and low tides. Second, the duration of downstream flow is about 8 hours; the duration of upstream flow is less than 4 hours. These durations are more and less than the expected 6.22-hour duration of a tidal phase unaffected by freshwater inflow. As freshwater inflow increases, the duration of downstream flow also increases.

Figure 2.5 shows typical variations of velocity with depth in the Cape Fear River. This particular profile was taken at the Atlantic Coast Line Railroad Bridge at Navassa (see figure 2.3) on May 13, 1966, during a series of discharge measurements on the Cape Fear River estuary. The manner of variation of velocity with depth is typical of hundreds of profiles made on this and other days. Velocities are very uniform with depth from within 5 or 10 feet of the surface down to within 5 or 10 feet of the channel bottom, then drop off sharply near the bottom. Velocities at the surface are usually only slightly less than at depths of 5 to 10 feet, but winds may cause near-surface velocities to increase or decrease. Point velocities due to tides alone in

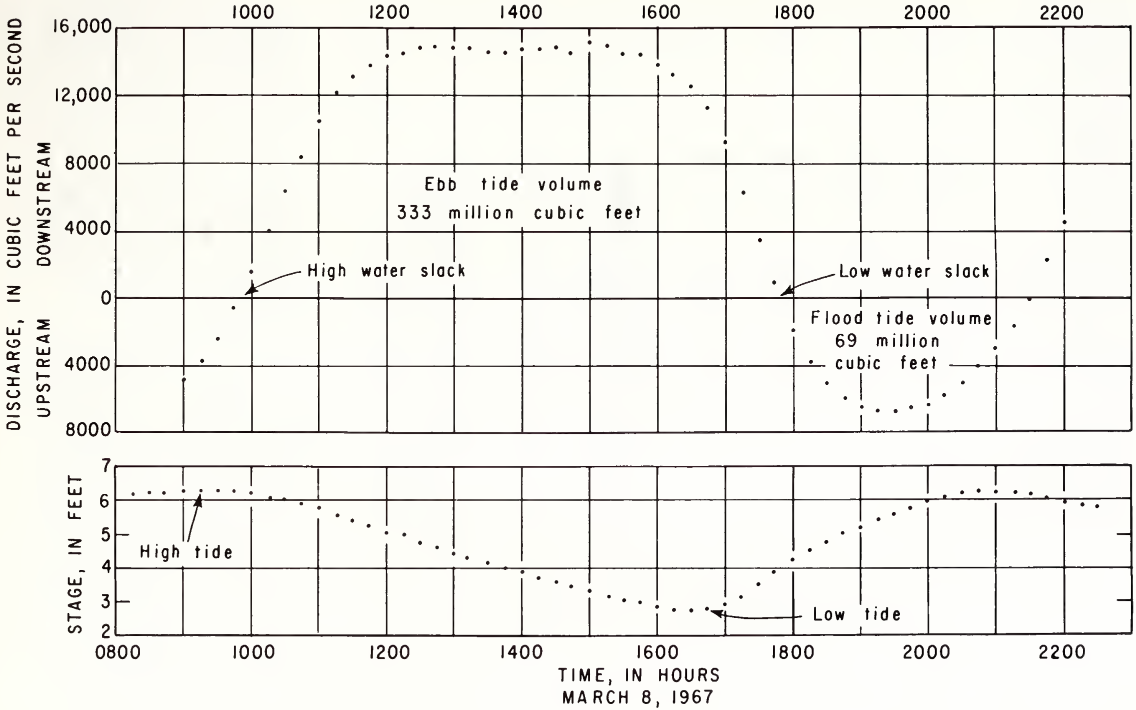


Figure 2.4.--Stage and discharge of the Cape Fear River estuary near Phoenix on March 8, 1967.

the Navassa-Phoenix reach seldom exceed 2 ft/s. The particle distance traveled up or downstream due to tides alone is in the range of 6 to 8 miles in this reach. Velocities and travel distances due to freshwater inflow would have to be added to those due to tides to determine actual velocities and travel distances in the estuary.

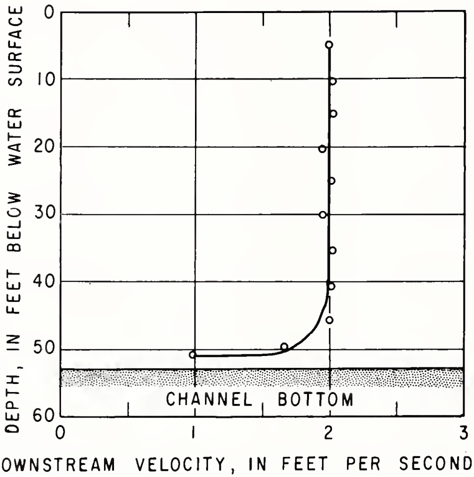


Figure 2.5.--Variation of velocity with depth of the Cape Fear River estuary at Navassa on May 13, 1966 (at meter station 20, 0759-0803 hours).

Water Quality

Summaries of water quality of inflowing freshwater at three key sites in the Cape Fear River basin are shown in table 2.1. Generally, minimum concentrations of dissolved constituents occur during high freshwater flows composed mostly of overland runoff, which is typically low in dissolved solids. Conversely, maximum concentrations of dissolved constituents tend to occur during minimum streamflows, which are composed largely of more-highly-mineralized ground water. Except for color and iron, concentrations of major constituents of incoming freshwater fall within limits for drinking water recommended by the Environmental Protection Agency (1976) [1978]. However, the North Carolina Office of Water and Air Resources (1972, p. 27-103) states that the

Table 2.1.--Summary of chemical analyses of freshwater samples collected at key stations in the Cape Fear River basin. From Wilder and Slack, 1971a. Chemical constituents shown are in milligrams per liter, except specific conductance, pH, and color.

Station number	Station name	Drainage area mi²	Period of sampling	Sampling frequency	Extremes and average	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids		Hardness as $CaCO_3$		Specific conductance (Micromhos at 25°C)	pH	Color
																		Residue at 180°C	Calculated	Calcium, magnesium	Non-carbonate			
02105500	Cape Fear River at William O. Huske Lock (Lock 3) near Tarheel, N.C.	4,810	Oct. 1946 to Sept.1967	daily	Max	13	0.35	5.5	2.2	21	2.6	e47	14	15	0.5	4.0	0.69	87	75	21	8	142	8.8	80
					Min	1.6	.01	2.0	.6	2.7	.6	8	2.5	3.2	.0	.0	.00	41	30	10	0	45	5.8	3
					Avg	7.6	.06	3.5	1.3	8.0	1.5	18	6.2	6.7	.2	1.0	.18	52	44	14	2	77	.....	35
02106500	Black River near Tomahawk, N.C....	680	Oct. 1952 to Sept.1967	monthly	Max	12	.94	5.2	1.9	8.2	2.2	17	14	7.7	.3	2.3	.10	70	48	19	17	85	7.0	220
					Min	2.6	.01	1.4	.2	2.5	.7	3	2.1	2.5	.0	.0	.00	44	23	6	1	37	5.1	20
					Avg	7.2	.21	3.1	.9	4.4	1.1	7.7	5.4	6.2	.7	.6	.03	56	33	11	5	53	.....	74
02108000	Northeast Cape Fear River near Chinquapin, N.C.	600	Oct. 1950 to Sept.1967	monthly	Max	14	.83	17	3.3	33	3.7	47	29	52	.5	6.9	.10	163	92	56	52	267	7.6	200
					Min	1.3	.01	2.8	.2	.7	.2	4	.8	3.6	.0	.0	.00	32	23	9	2	39	5.1	30
					Avg	6.9	.25	5.3	1.2	8.6	1.2	14	5.8	14	.2	1.6	.03	70	48	18	8	85	.....	89

rapid industrialization which has taken place along the Cape Fear River estuary, particularly by chemical industries, has resulted in a variety of chemical substances being discharged into it, rendering it unfit, even where fresh, for drinking and some other uses without expensive treatment. The report further states that synthetic organic compounds released into the estuary by petrochemical industries may be a particularly difficult treatment problem because these compounds resist destruction by communities of micro-organisms used to treat ordinary sewage in waste treatment plants. Heating of the estuary water from power-plant operations and industrial-cooling operations may be a significant problem along some reaches. If not for contamination, the water, where fresh, would be suitable for most industrial, domestic, and agricultural uses.

Superimposed on difficulties in freshwater use due to contamination are difficulties due to saltwater intrusion, which may at times affect water quality as far as 20 miles upstream from Wilmington. Details of saltwater intrusion in the estuary are given later.

Sediment

The Geological Survey has made suspended-sediment determinations from monthly samples collected at Lock 1 near Kelly (station number 02105769 on plate 1) since January 1973. The average suspended-sediment load there is about 920 tons/day or 336,000 tons/year. Particle-size analyses (Simmons, 1976) show that over 90 percent of this material is of silt or clay size (.062 mm or less). The fate of this sediment has not been completely studied, but it is known that some is deposited in the estuary. The U.S. Army Corps of Engineers estimates that, in order to maintain navigation facilities at the Military Ocean Terminal at Sunny Point (MOTSU), about 18 miles downstream from Wilmington, 2,238,000 cubic yards, or about 3.5 million tons, of sediment must be removed annually at a cost of $2,169,000 (U.S. Army Corps of Engineers, 1976, p. 4). This gives some idea of the economic impact of sedimentation in the estuary.

Note, from the above discussion, that the amount of material removed from the estuary through dredging far exceeds the amount entering by way of Lock 1. Additional fluvial sediment entering the estuary from the Northeast Cape Fear River and other sub-basins probably does not exceed 35,000 tons/year. Therefore, the primary source of the new shoaling in the Sunny Point area could not be new fluvial sediment, but must be derived from within the estuarine reach or elsewhere--from slumping along the channel, from shore erosion, from old spoil areas, or possibly from sediment derived from the ocean.

Salinity

Variations in time and space.--The Cape Fear River may be classified under some flow conditions as a partially mixed estuary. That is, turbulence is sufficient to prevent formation of a distinct saltwater wedge or tongue, yet there remains a definite salinity gradient with depth. This is illustrated in figure 2.6, which shows typical longitudinal variations in chloride concentrations of the Cape Fear River at a high-slack tide on November 1, 1967. The gradient is accounted for by the density differences between fresh and saltwater. The less dense freshwater tends to flow on top of the heavier saltwater. These density differences are also responsible for upstream density currents which may occur along the channel bottom. These have been observed at and near the Military Ocean Terminal at Sunny Point where a predominant upstream or flood flow exists at times in the lower portions of the river water column (U.S. Army Corps of Engineers, 1976, p. 2).

A different view indicative of salinity stratification is shown in figure 2.7, which is a cross-section showing chloride concentrations of the Cape Fear River estuary 1.5 miles upstream from Market Street, Wilmington, on June 5, 1962. The top-to-bottom differences are very marked. The surface concentration of 150 mg/L of chloride is equivalent to less than one percent sea water while the bottom concentration of 3,000 mg/L or greater is at least 16 percent that of seawater.

The salinity of the estuary is in a state of constant flux. Saline water moves in and out of the Cape Fear estuary regularly in response to tidal action, freshwater inflow, winds, and a number of other, less significant, factors. However, it has been found, at least for the part of the estuary above Wilmington, that the relative positions of the various lines of equal chloride concentration are fairly constant. In other words, if we know the river mile position of 300 mg/L of chloride, then the position of 200 or 1,000, or 3,000 mg/L of chloride may be predicted with a fair degree of accuracy, provided that the locations are somewhere above Wilmington. This relation is shown in figure 2.8. The values given are for the channel bottom at high slack tide. Values at the surface would be somewhat less.

The maximum upstream movement of saltwater in the Cape Fear River estuary probably occurred during the passage of Hurricane Hazel on October 15, 1954. The eye of the hurricane moved inland near the South Carolina border and proceeded in a northerly direction along a path that crossed the upper end of the estuary. The counterclockwise circulation of winds around the hurricane eye produced strong winds from the southeast which raised tides to the highest level ever recorded at Wilmington. The high tide measured at the National Ocean Survey's Wilmington gage was 7.9 feet above mlw (mean low water); the next highest recorded tide, corrected for river stage, is only 5.6 feet above mlw. (See fig. 2.10.) Although the position of the saltwater front during the passage

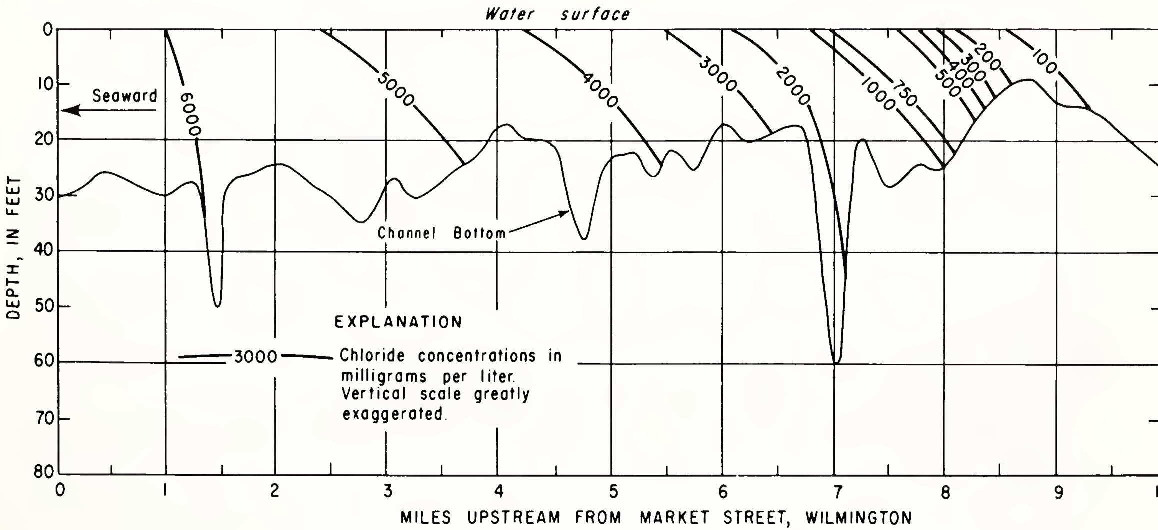


Figure 2.6.--Longitudinal variations in chloride concentrations of the Cape Fear River estuary at high-slack tide, November 1, 1967. From Wilder and Hubbard, 1968. (Refer to fig. 2.3 for locations.)

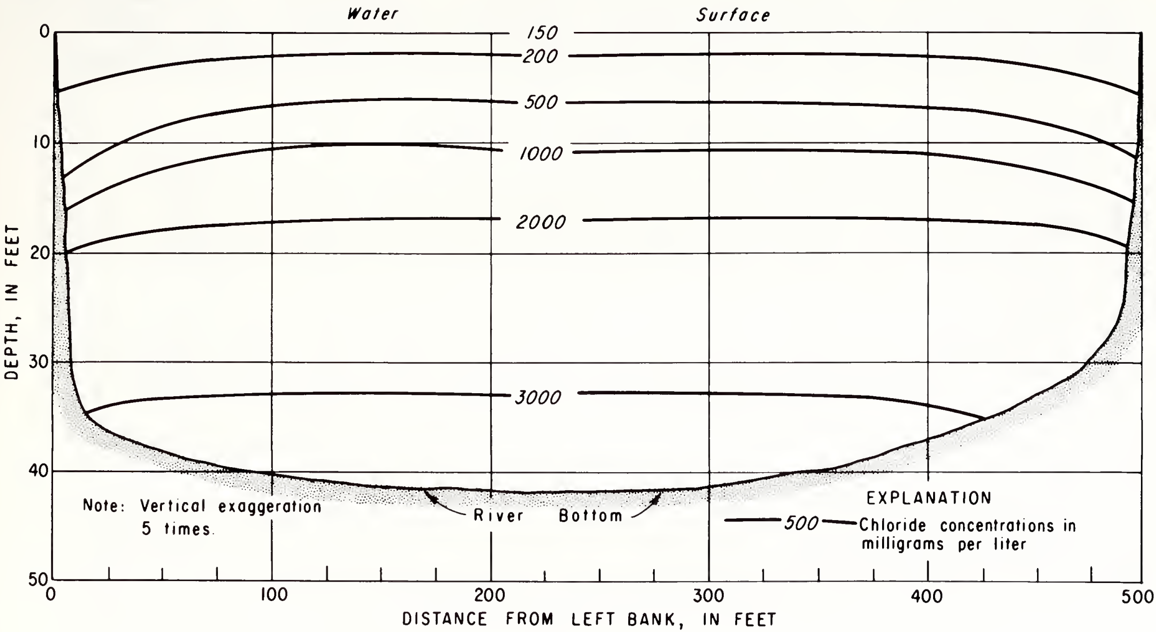


Figure 2.7.--Variations in chloride concentrations in a cross section of the Cape Fear River estuary 1.5 miles upstream from Market Street, Wilmington, on June 5, 1962. From Wilder and Hubbard, 1968.

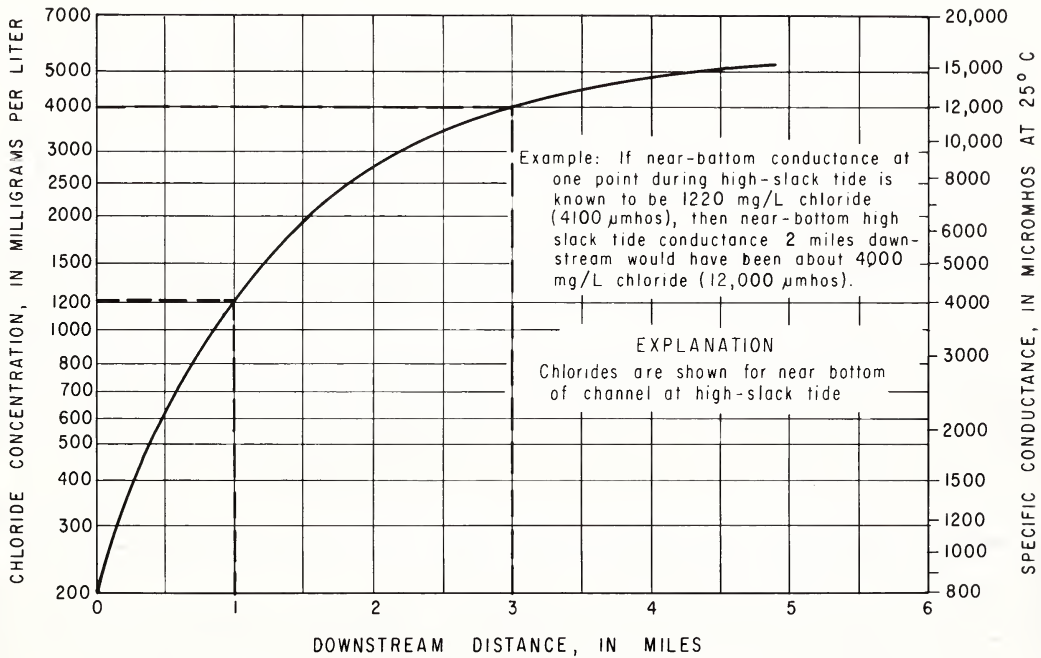


Figure 2.8.--Relation between chloride concentration and specific conductance at a known point in the Cape Fear River estuary and chloride concentration and specific conductance at other points either upstream or downstream. Relation applies only to reaches upstream from Wilmington.

of Hurricane Hazel was not observed, it is estimated that it reached a position more than 20 miles above Wilmington (plate 1). At the same time, it is estimated that the saltwater front on the Black River, a major tributary to the Cape Fear River, reached a position about 15 miles upstream from its mouth (plate 1). The freshwater inflow to the estuary as measured at Lock 3 during the seven days preceding the hurricane averaged about 290 ft^3/s. This is the lowest estimated inflow during the period of record (1938-1978) at Lock 3. This accounts, in part, for the extreme encroachment of the front which, it is inferred, must have taken place on October 15, 1954.

The movement of the saltwater front in response to semidiurnal tides is of particular importance to industries and others withdrawing water from reaches of the river which may be subject to saltwater intrusion. By carefully scheduling withdrawals, it is often possible to obtain freshwater from the estuary throughout much of each tidal cycle. High-slack tide, bottom-chloride conditions given in figure 2.8 represent the highest chloride concentrations which usually occur during a tidal cycle and are of relatively short duration. Figure 2.9 shows the approximate number of hours during a tidal cycle that near-bottom chloride concentrations may be expected to exceed 200 mg/L for various maximum concentrations at high-slack tide. It is important to note that this relation applies only upstream from Wilmington. This figure shows that, unless the chloride concentration at high-slack tide exceeds approximately 5,500 mg/L, it is possible to obtain freshwater from the estuary for some part of the tidal cycle. For example, it indicates that with a maximum chloride concentration at high-slack tide of about 2,000 mg/L, it is possible to obtain freshwater for about 7 hours of the total 12.42-hour tide cycle.

Relation of salinity to freshwater inflow and tides.--The distances upstream and downstream that the saltwater front moves in response to tides depends of course on the volumes of water transported by the tides. These volumes are reflected, in a general way, by the relative heights of high and low tides. Other factors being equal, the higher the tide, or series of tides, the farther upstream the front will move. Thus, tide heights can serve as useful indexes to semidiurnal saltwater movements.

The National Ocean Survey (formerly the U.S. Coast and Geodetic Survey) has operated a tide gage at Wilmington since 1935. Data on tidal heights were also obtained by the Geological Survey at its stage stations on the Cape Fear River near Phoenix and Navassa, from April 1966 through March 1969. Figure 2.10 shows the number of years the observed highest annual tide equaled or exceeded indicated heights above mean low water at Wilmington during 1935-66. Neglecting the effect of serial correlation, the probability of occurrence of a highest annual tide of a given magnitude at Wilmington can be estimated from this curve.

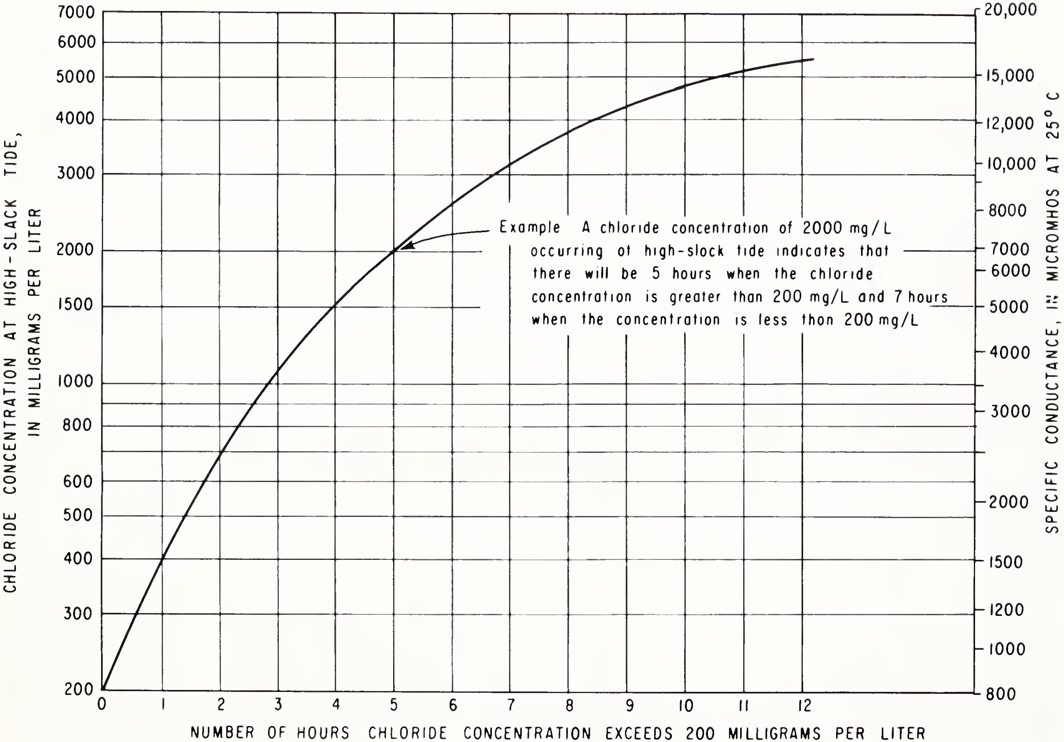


Figure 2.9.--Relation between chloride concentration near the bottom of the Cape Fear River estuary upstream from Wilmington at high-slack tide and the number of hours the chloride concentration will exceed 200 mg/L near the channel bottom. From Wilder and Hubbard, 1968.

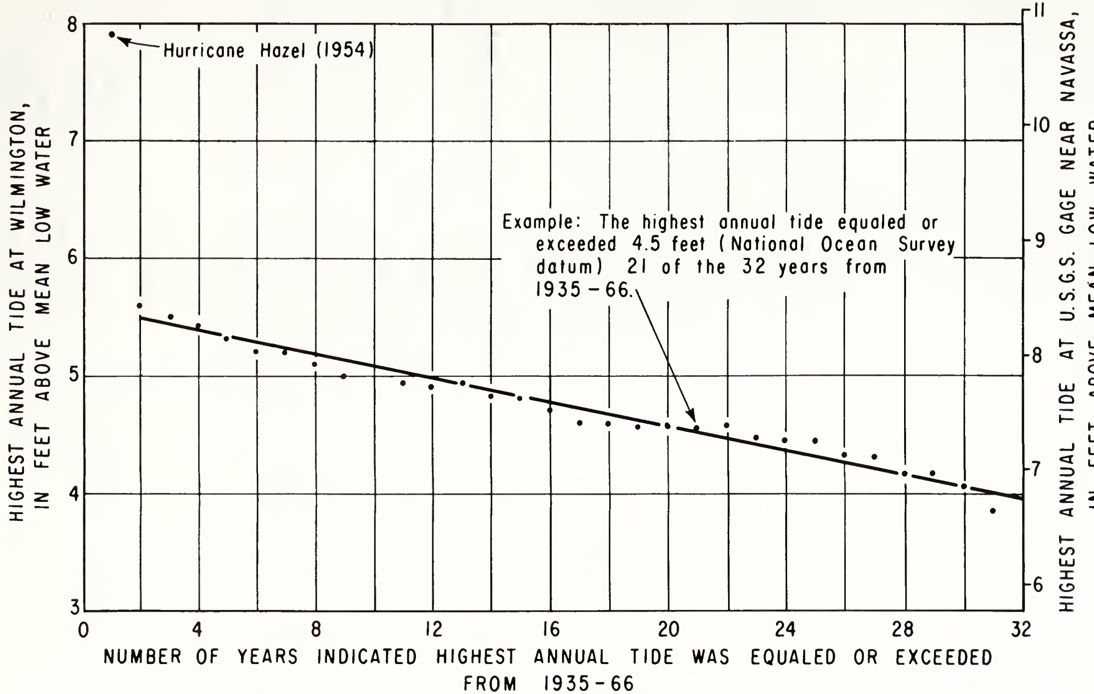


Figure 2.10.--Magnitude and frequency of highest annual tide in the Cape Fear River estuary at Wilmington, corrected for component of river stage due to freshwater inflow. From Wilder and Hubbard 1968.

Wilder and Hubbard (1968) related the position of the saltwater front at high-water slack tide to the previous 7-day average freshwater discharge at the mouth, as determined from gaging station data and the use of fig. 2.1 and equation 2.1. They were able to adjust the relation for the effects of varying tide heights. Details of the development of these relations are contained in their report, but the final relation is presented in figure 2.11. This figure contains a family of curves for selected tide heights showing the estimated position of the saltwater front for different rates of inflow. Approximate results may be obtained by interpolation between the curves.

Frequency of occurrence of minimum annual inflows and highest annual tides have been presented earlier in figures 2.2 and 2.10. Combining data from these figures to obtain the maximum annual encroachment of the saltwater front presents several problems. Two of the more salient of these are (1) the non-random distribution of tide height and inflow during a year, and (2) the possibility of the simultaneous occurrence of high tides and low inflow, neither of which are annual extremes, but which, in combination, may produce the maximum encroachment. However, if one of these parameters is held constant, probabilities may be determined with reasonable accuracy. For example, using figure 2.11 and assuming that the maximum tide will be 4.0 feet above mean low water during the period of annual minimum flow, it may be that encroachment to a point 10 miles above Wilmington will occur when the 7-day average outflow is about 820 ft^3/s, and we estimate from figure 2.2 that such a flow condition will recur on an average of 3.8 years.

It is apparent, from figure 2.11 that saltwater encroachment will not be a problem as far upstream as 15 miles above Wilmington, near the mouth of the Black River, without the simultaneous occurrence of both an exceptionally high tide and an exceptionally low inflow.

Another important factor that may eventually affect the extreme annual position of the saltwater front is the B. Everett Jordan Reservoir. Plans for this reservoir provide for a minimum flow of 600 ft^3/s in the Cape Fear River at Lillington. This reservoir release, plus the minimum inflow that may be expected to occur about once in 100 years, on average, between Lillington and the mouth, will produce about 800 ft^3/s of outflow from the estuary. This augmented flow may considerably reduce the maximum extent of saltwater encroachment in the estuary.

The Northeast Cape Fear River Estuary

The Northeast Cape Fear River (see plate 1 and fig. 2.12) heads in Wayne County, flows south through Duplin, Pender, and New Hanover Counties, and at Wilmington flows into the Cape Fear River, which empties into the ocean about 30 miles south of Wilmington. The total area drained is 1,740 mi^2. The entire basin lies within the Coastal

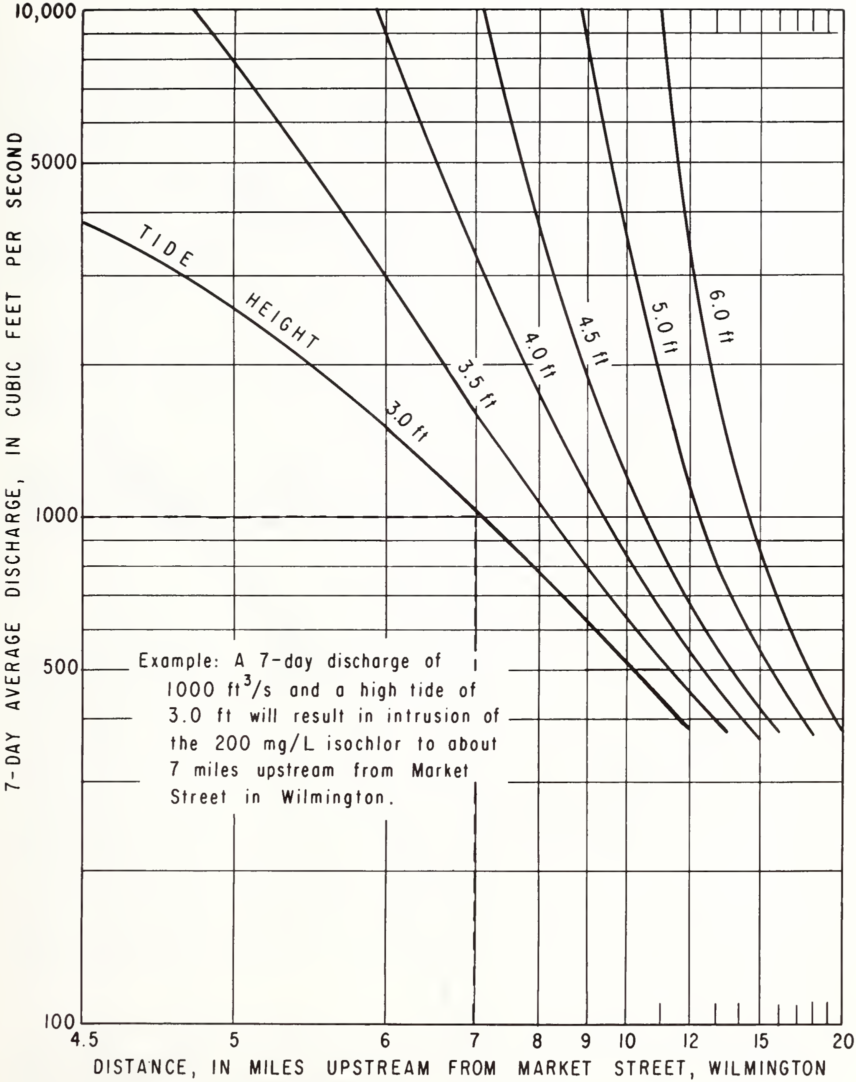


Figure 2.11.--Interrelations of maximum encroachment of 200 mg/L chloride, outflow at the mouth, and tide heights in the Cape Fear River estuary. Revised version of relation developed by Wilder and Hubbard, 1968.

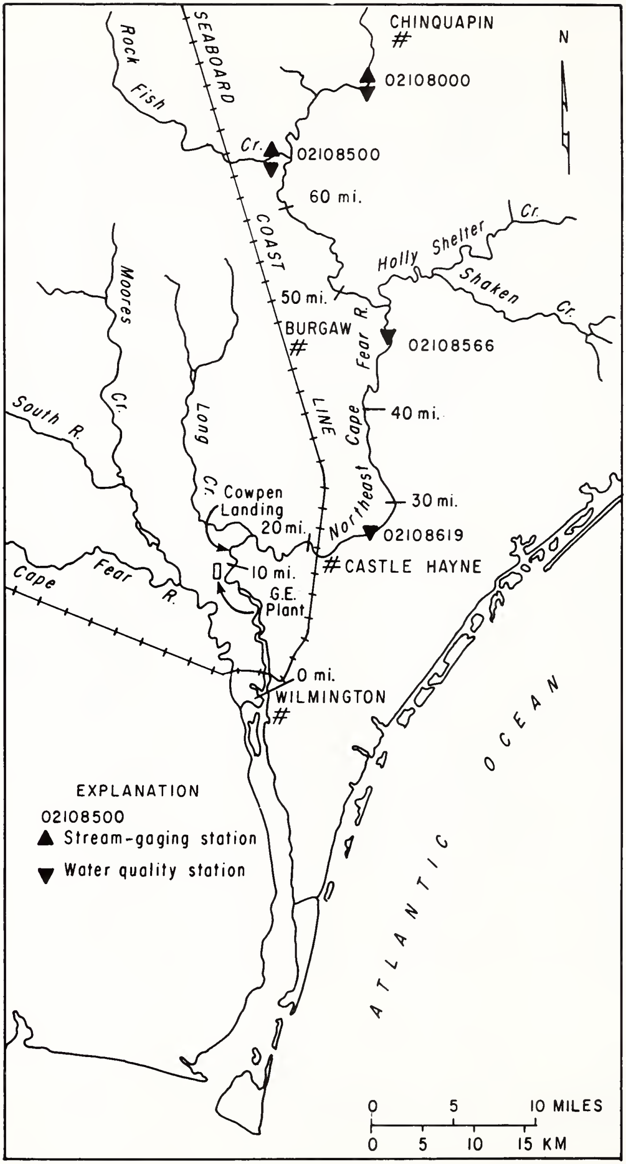


Figure 2.12.--Northeast Cape Fear River estuary.

Plain and stream gradients average less than one-half foot per mile. The two largest tributaries are Rockfish Creek and Holly Shelter Creek. Much of the main stem of the Northeast Cape Fear River and most of its tributaries are typical black-water, swamp-drainage streams, with imperceptible flows, sand-detritus bottoms, and low turbidity. Tide effects in the Northeast Cape Fear River extend upstream almost 50 miles from the mouth, to near Holly Shelter Creek. Thus, the river may be considered an estuary in that 50-mile reach. Many of the tributaries entering the Northeast Cape Fear River in its tidal reach are also affected by tides.

The lower 2.5 miles of the Northeast Cape Fear River estuary has been dredged and a navigation channel 32 feet deep and 300 feet wide is maintained. Upstream from this, to a point 48 miles above the mouth, the river was cleared to a depth of 6 feet in 1896; upstream from this, to 56 miles above the mouth, the river was cleared to a depth of 3 feet.

Several industries use the Northeast Cape Fear River and its tributaries both as a source of process water and as a conveyor of industrial wastes. The upper reaches of the Northeast Cape Fear River are used for recreation, primarily boating and fishing.

Freshwater Inflow

The average net outflow of the Northeast Cape Fear River estuary is about 2,120 ft^3/s. Of greater interest than average flow, however, are low flows, because pollution and saltwater intrusion problems are greatest during low flows. In the Northeast Cape Fear River, an attempt to estimate low flows at the mouth by simple extrapolation of the measured low flow at Chinquapin, based on drainage-area ratios, will lead to erroneously high results. This is because, during low-flow periods, the upper part of the basin contributes a proportionately higher percentage of flow than does the lower part of the basin. For this reason, a relation was developed by Hubbard and Stamper (1972, p. E21) relating the low flow at Chinquapin to the flow at the mouth. The relationship, shown in figure 2.13, provides a reliable approximation of total freshwater flow out of the Northeast Cape Fear River only during stable low-flow recessions, when flow at Chinquapin is less than 360 ft^3/s. Therefore, the relationship should not be extended beyond the limits shown.

Another important aspect of low flows is frequency of recurrence. Figure 2.14 shows low-flow frequency curves of net outflow from Hubbard and Stamper (1972). These curves may be used to estimate the frequency of recurrence of various annual minimum consecutive-day average outflows. For example, a minimum annual 7-consecutive-day average inflow of about 15 ft^3/s or less is expected to have an average recurrence interval of about 10 years. The flow relations presented in this

section of the report can be used, as discussed later, to develop relations showing the frequency of recurrence of saltwater intrusion in the Northeast Cape Fear River estuary.

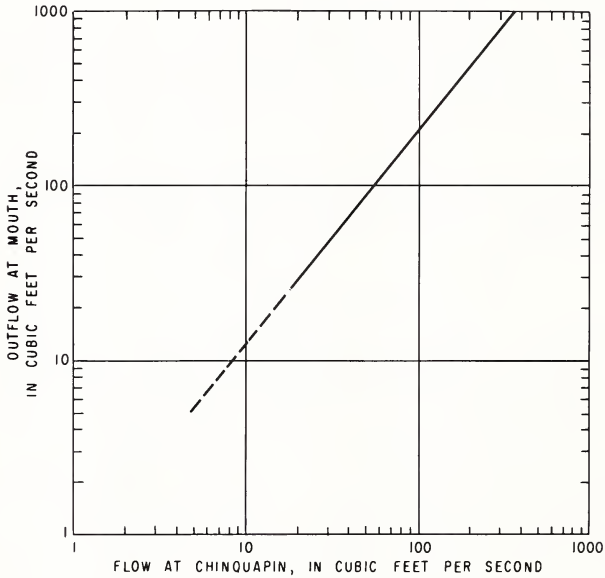


Figure 2.13.--Relation between flow measured at Northeast Cape Fear River at Chinquapin and net outflow from the Northeast Cape Fear River estuary at the mouth. Adapted from Hubbard and Stamper (1972).

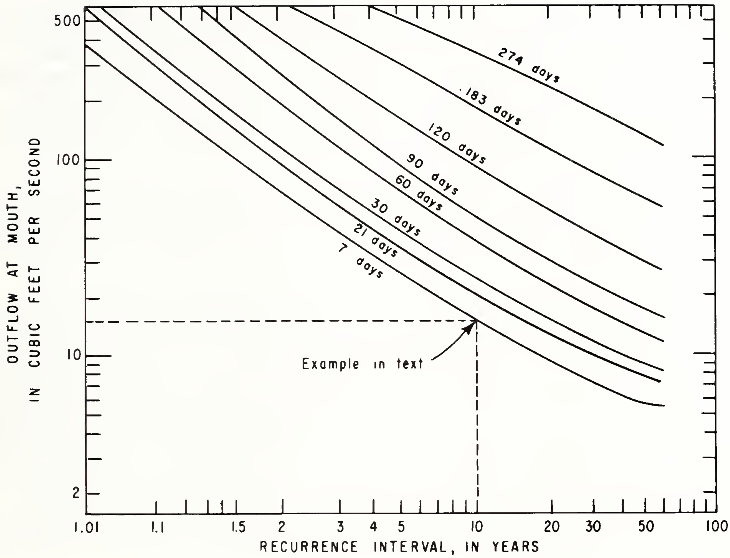


Figure 2.14.--Low-flow frequency curves for the Northeast Cape Fear River estuary. Adapted from Hubbard and Stamper (1972).

Tide-Affected Flow

Tide ranges in the Northeast Cape Fear River estuary vary considerably depending on distance upstream from the mouth at Wilmington, as shown in the following table:

Miles from mouth of Northeast Cape Fear River estuary	Location	Mean tide range in feet
6.4	at General Electric Company plant	3.4
about 23	near Castle Hayne	1.7

Flow due to tides is the dominant flow component in the lower reaches of the Northeast Cape Fear estuary. Strong flow reversals occur near the mouth with each tidal cycle. Here, river velocities due to tides average about 1-1.5 ft/s, and seldom exceed 2 ft/s. Although no specific information is available on velocities due to tides in the upper reaches of the Northeast Cape Fear River Estuary, presumably they would become insignificant near river mile 50.

The average freshwater inflow to the estuary is about 2,100 ft^3/s. At this rate, average velocities near the mouth due to freshwater inflow alone are only about 0.08 ft/s, or 5 to 8 percent of the average velocities attributable to tides.

The U.S. Geological Survey made a continuous measurement of tide-affected discharge during one complete tidal cycle, 6.4 miles upstream from the mouth of the Northeast Cape Fear estuary, on October 23, 1969. The results of the measurement are shown in figure 2.15. The maximum discharge measured on October 23 was 22,250 ft^3/s. This occurred during flood tide at 1930 hours. The maximum discharge measured on ebb tide was 18,080 ft^3/s at 1400 hours. These values are much larger than the estimated 420 ft^3/s of freshwater inflow for that day. During ebb tide, a total of 315 million cubic feet of water flowed past the measuring section. Of this amount, only about 11 million cubic feet could be accounted for by freshwater inflow to the estuary. This represents about 3 percent of the total flow volume.

Obviously, tides are the dominant short-term flow component near the mouth of the Northeast Cape Fear River estuary. A freshwater inflow of about 23,000 ft^3/s, almost 11 times the average, would have been required to prevent flow reversals during the October 23 measurements, and flows as large or larger than 23,000 ft^3/s occur only about 0.02 percent of the time. Further upstream, the influence of tides on flow is less and becomes negligible about 50 miles upstream.

As in the case of the Cape Fear River estuary, times of high and low tides in the Northeast Cape Fear River estuary do not coincide with times of slack water, as shown in figure 2.15. During the October 23 measurement, slack water occurred more than an hour after high and low tides.

Detailed vertical velocity profiles are not available for the Northeast Cape Fear River estuary. However, based on some velocity observations made during the October 23 measurement, profiles would be similar to those observed during measurements of the Cape Fear River estuary, shown earlier in figure 2.5.

During October 1969, a study of the movement and dispersion of dye in the Northeast Cape Fear River estuary was made by the U.S. Geological Survey. The results of this study are contained in the 1972 report by

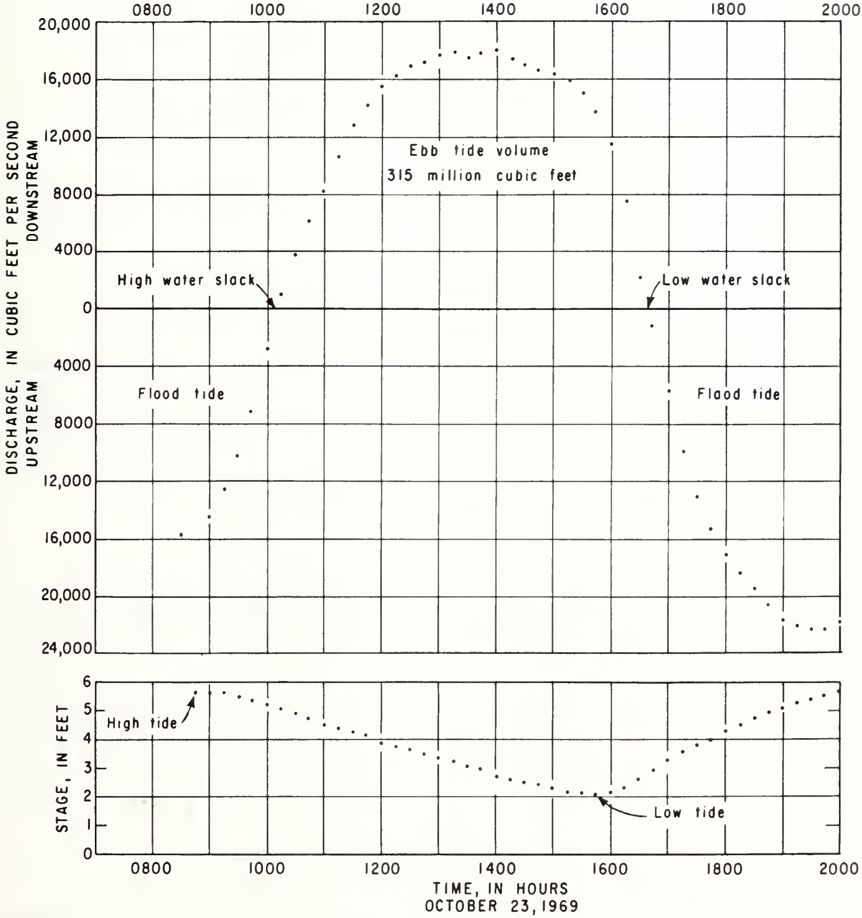


Figure 2.15.--Stage and discharge as measured continuously during October 23, 1969, in the Northeast Cape Fear River estuary, 6.4 miles upstream from the mouth.

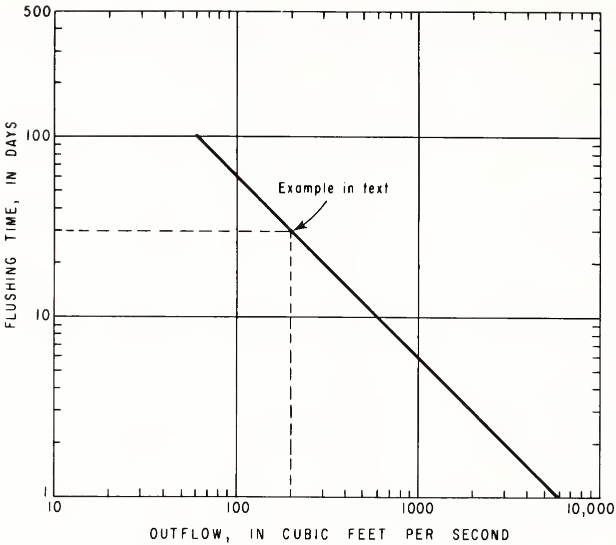


Figure 2.16.--Average flushing time for a solute injected into the Northeast Cape Fear River estuary about 6.5 miles upstream from the mouth. (From Hubbard and Stamper, 1972.)

Hubbard and Stamper. Figure 2.16, taken from that report, shows average flushing times for a solute injected into the estuary about 6.5 miles upstream from the mouth. When a solute (or pollutant) is injected as a slug, it travels upstream and downstream with flood and ebb flows. As it does so, it spreads out and becomes diluted, forming a cloud of the solute. In addition to the upstream-downstream movement of the cloud due to tidal flows, there is a net downstream movement of the cloud due to freshwater inflow. This cloud has a center of mass and it is the flushing time of the center of mass to which figure 2.16 refers. For example, referring to figure 2.16, if the outflow is 200 ft^3/s, it would take 30 days for the center of mass to reach the mouth from 6.5 miles upstream. At this time, one-half of the solute would already have passed the mouth and one-half would not yet have reached the mouth. The results of this analysis can be extended upstream and downstream for different injection points by using cross-sectional areas and average freshwater inflows. Then, mean velocities for a given reach may be determined by the equation:

$$V = \frac{Q}{A} \tag{2.2}$$

where

V = mean velocity, in feet per second through the subreach

Q = freshwater inflow, in cubic feet per second

A = area, in square feet

Dividing the length of each subreach by the mean velocities gives net traveltimes, which are based on freshwater inflow, disregarding tidal effects.

Hubbard and Stamper (1972) also give maximum concentration buildups at various river cross-sections due to various constant injection rates of a solute 6.5 miles upstream from the mouth. They found that the dye cloud dispersed upstream and downstream several miles from the injection point but that maximum solute concentration buildup was only 0.3 miles below the injection point. It is difficult to extrapolate their results upstream or downstream for other injection points in the Northeast Cape Fear River estuary, but maximum concentration buildups would be expected near the injection points.

Water Quality

Summaries of the chemical quality of water at three key sites in the Northeast Cape Fear River basin are given in table 2.2, including observed ranges and average values of major chemical constituents. Iron concentrations sometimes exceed the 0.3 mg/L concentration limits recommended by the Environmental Protection Agency (1976) [1978] for public water supplies. The same is true for color, which often exceeds the upper limit of 75 color units recommended by the Environmental Protection Agency (1976) [1978]. The color of the Northeast Cape Fear River is derived primarily from decaying vegetation and the leaching of humic acids in swamp areas.

Sediment

The sediment-carrying capacity of the Northeast Cape Fear River and its tributaries is low due to low stream gradients. Most of the sediment that is carried is of clay or silt size (less than 0.062 mm). Based on flow and sediment measurements made at Northeast Cape Fear River at Chinquapin and Rockfish Creek near Wallace, the average annual sediment inflow to the estuary is probably no more than about 15,000 tons (20,000 cubic yards). This amount is less than one-third of the estimated 66,000 cubic yards of sediment that the U.S. Army Corps of Engineers removes on an average annual basis from the Northeast Cape Fear River estuary to maintain navigation.

Table 2.2.--Summary of chemical analyses of water samples collected at key stations in the Northeast Cape Fear River basin (adapted from Wilder and Slack, 1971a). Chemical constituents are in milligrams per liter, except specific conductance, pH, and color.

Station number	Station name	Drainage area in mi^2	Period of sampling	Sampling frequency	Extreme and average	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids		Hardness as $CaCO_3$		Specific conductance (Micromhos at 25°C)	pH	Color
																		Residue at 180°C	Calculated	Calcium magnesium	Non-carbonate			
02108000	Northeast Cape Fear River near Chinquapin, N.C.	600	Oct. 1950 to Sept. 1967	daily	Max	14	.83	17	3.3	33	3.7	47	29	52	.5	6.9	.10	163	92	56	52	267	7.6	200
					Min	1.3	.01	2.8	.2	.7	.2	4	.8	3.6	.0	.0	.00	32	23	9	2	39	5.1	30
					Avg	6.9	.25	5.3	1.2	8.6	1.2	14	5.8	14	.2	1.6	.03	70	48	18	8	85	...	89
02108566	Northeast Cape Fear River near Burgaw, N.C.	about 920	Oct. 1963 to Sept. 1965	daily	Max	10	.45	10	1.8	21	2.3	29	13	34	.3	3.4	.86	126	94	30	13	170	7.4	160
					Min	2.7	.00	3.5	.1	3.9	.6	6	3.2	4.5	.0	.3	.00	46	29	12	0	48	6.0	100
					Avg	6.6	.18	6.0	1.1	9.1	1.3	15	7.4	14	.1	1.1	.24	72	59	19	7	87	...	55
02108619	Northeast Cape Fear River near Castle Hayne, N.C.	about 1500	Oct. 1959 to Sept. 1967	daily	Max	18	1.0	27	2.9	21	4.1	74	16	41	.4	4.8	.30	138	122	73	18	203	8.3	340
					Min	2.1	.00	3.7	.3	2.0	.1	8	1.1	4.0	.0	.0	.00	17	29	13	0	46	5.6	50
					Avg	6.1	.23	7.1	1.1	6.3	1.1	19	6.1	9.9	.2	1.3	.11	76	48	22	8	77	...	153

Obviously, the amount of sediment from upstream sources is not enough to account for the amount of maintenance dredging that is done in the estuary. The question then arises, what is the source of the sediment that forms shoals in the navigation channel and harbor facilities in the Northeast Cape Fear River estuary? This question can be answered only speculatively because little actual work has been done to determine the exact sources. Probably only a part of the estimated 20,000 cubic yards of sediment that is carried into the estuary by freshwater inflow actually settles in the estuarine zone. Likely, a large proportion of it is carried out into the Cape Fear River estuary. However, sediment that is deposited from upstream sources would tend to settle in the deeper dredged areas.

A second possibility is that some shoaling materials may be transported upstream from the Cape Fear River. This could occur whenever the Northeast Cape Fear estuary is in a partially-mixed or stratified state. Then, net upstream flow might prevail near the bottom. The minimum mixing ratio needed to produce partially-mixed conditions is about 0.5. (Refer to discussion on estuarine types in Chapter 1--GENERAL HYDROLOGY.) Based on measurements of tide-affected flow in the estuary, the minimum freshwater inflow needed to produce partially-mixed conditions (and, hence net upstream velocities near the channel bottom) would be about 6,500 ft^3/s. Although freshwater inflows of this magnitude or greater occur less than 5 percent of the time, it is possible that significant upstream migration of shoaling materials occurs due to this phenomenon.

The third and possibly the major source of shoaling materials is within the estuarine reach itself. These sources could include materials eroded from the shores, materials resuspended from the channel bottom and moved by tidal action to the shoaling areas, and slumping of materials adjacent to the navigation channel.

Salinity

Variations in time and space.--With respect to salinity, the Northeast Cape Fear River estuary may be classified as a well-mixed estuary, for most of the time, at least. This has been verified by several specific conductance surveys, one of which is summarized in figure 2.17. This figure shows lines of equal specific conductance along a channel profile of the Northeast Cape Fear River estuary, based on data collected on November 9, 1966. There was very little difference on that day between surface and bottom specific conductances in most of the reach portrayed here. The mixing index was estimated to be about 0.06 for that day, which is very close to the arbitrary upper limit of 0.05 for a well-mixed estuary. Although no extensive specific conductance data were collected within any cross-section on that day, it is not likely that any significant specific conductance differences existed within cross-sections.

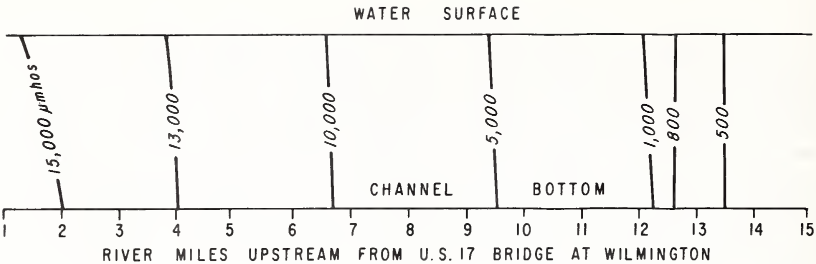


Figure 2.17.--Longitudinal variations in specific conductance of the Northeast Cape Fear River estuary on November 9, 1966. Depths are variable and should not be inferred from the sketch.

Historically, the maximum observed upstream intrusion of saline water into the Northeast Cape Fear estuary occurred during Hurricane Hazel on October 15, 1954, when chloride concentrations reached 1,450 mg/L at Castle Hayne. Based on this and information in fig. 2.18 (discussed later), the saltwater front could have been 2 or 3 miles upstream from Castle Hayne on that date.

The very extreme saltwater encroachment which took place due to Hurricane Hazel was in addition to the extreme encroachment which had already taken place due to record low river flows immediately preceding the hurricane. At Chinquapin, for example, the discharge averaged only 5.3 ft^3/s on October 10-11, 1954, the all-time low for the 37-year period of record. On October 9 and 10, 1954, chloride concentrations were already about 500 mg/L at Castle Hayne, the greatest salinity intrusion of record, up to that time. The recurrence interval of two such rare events occurring in succession is not known, but it may be reckoned in centuries.

The maximum seaward movement of the saltwater front occurs during times of high freshwater inflow, usually in the spring. At such times, the front may be displaced out of the Northeast Cape Fear River estuary altogether, leaving the estuary completely fresh for a short period.

It is not economically feasible on a routine basis to survey the entire river to locate the saltwater front. However, based on previous salinity surveys, a type curve has been developed for the Northeast Cape Fear River estuary which may be used to estimate the specific conductance at any point in the estuary, if the specific conductance is known at only one point (fig. 2.18). As an example of the use of this type curve, suppose that the specific conductance near the channel bottom at a high-slack tide is 6,000 µmhos at Cowpen Landing, 11.2 miles upstream from the U.S. Highway 17 bridge in Wilmington, (U.S. Highway 17 bridge

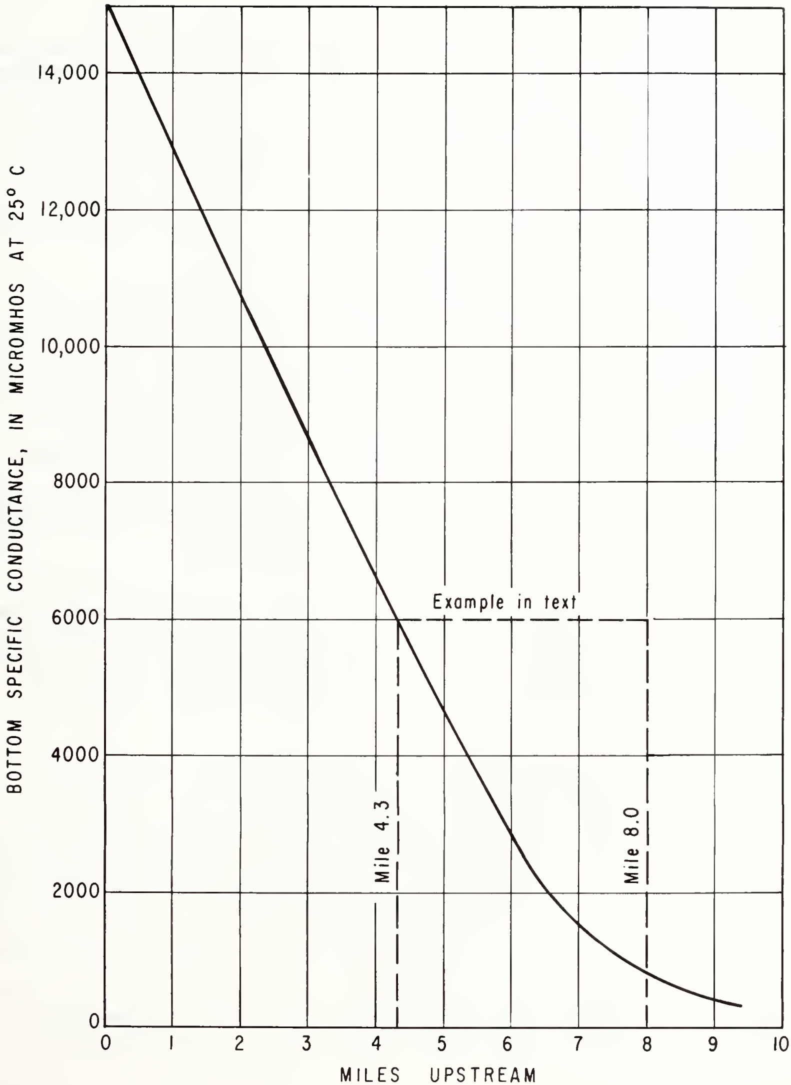


Figure 2.18.--Specific conductance type curve for the Northeast Cape Fear River estuary.

is about 0.85 miles upstream from the mouth of the estuary) and we want to know the location of the saltwater front (800 μmhos). To determine this, first find the miles upstream value on the abscissa corresponding to the 6,000 μmho value of the ordinate. This value is 4.3 miles. Next, find the abscissa value corresponding to the ordinate value of 800 μmhos. This value is 8.0 miles. The distance upstream from the 6,000 μmhos location to the 800 μmhos location is 8.0 - 4.3, or 3.7 miles. Because Cowpen Landing is at the 11.2 river mile point we would expect on that date to find the saltwater front near the channel bottom at the 14.9 river mile point (11.2 + 3.7 = 14.9).

Relation of salinity to freshwater inflow.--The relation of salinity to freshwater inflow to the Northeast Cape Fear River estuary is more complex than in most estuaries because it is affected by salinity conditions in the Cape Fear River estuary. Nevertheless, such a relation has been developed for the Northeast Cape Fear River estuary, which may be applied with useful accuracy to predict movements of the saltwater front. The relation (fig. 2.19) is based on the discharge at the Chinquapin gage and the location of the saltwater front during high-slack tide as observed during six salinity surveys made between August 1, 1955, and November 9, 1966. Of several flow parameters tried, the location of the saltwater front during high-water slack related best to the preceding 21-day average fresh-water discharge.

The scatter of data points in figure 2.19 may be due to several factors. One is that unusually large or small tidal ranges for a given day may result in correspondingly greater or lesser upstream incursions of saline water on that day. Secondly, the relation is influenced by winds, which, if blowing upstream, may result in greater-than-normal saltwater advances, and, if blowing downstream, in lesser saltwater advances.

Salinity conditions in the Cape Fear River estuary are a third factor influencing the scatter of points in figure 2.19. If, for example, high flows in the Cape Fear River basin due to a rainstorm occurring in that basin (but not in the Northeast Cape Fear River basin) displaced saline water downstream further than before the storm, this would also decrease salinities in the Northeast Cape Fear River basin to some degree. A fourth factor influencing the relation relates to a situation when the position of the saltwater front is not in equilibrium with freshwater inflow. This situation may exist when a period of high freshwater inflow is followed immediately by a period of much lower freshwater inflow. The saltwater front would immediately begin to move upstream in response to the diminished inflow, but may not reach an equilibrium position within the 21-day period used in developing the relation.

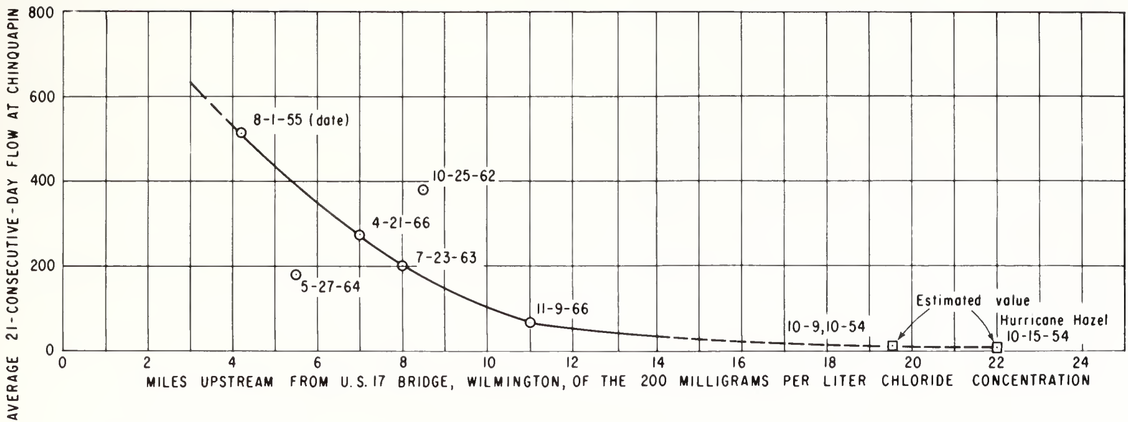


Figure 2.19.--Relation of the location of the saltwater front in the Northeast Cape Fear River estuary to the preceding 21-day average discharge at Chinquapin.

Regardless of these limiting factors, the relation can be used to roughly predict saltwater advances under a wide range of freshwater inflows as measured at Chinquapin. Such information could be useful, for example, in predicting whether or not saline water would reach a water-supply intake under prevailing inflow conditions. It may also be useful in locating future freshwater supply intakes where there is the least chance of saltwater intrusion.

For some potential users contemplating a water supply in the lower reaches of the Northeast Cape Fear River estuary, a certain degree of risk of saltwater intrusion may be acceptable in return for advantages gained by locating near waterborne transportation. To help evaluate this risk, a frequency of intrusion relation has been developed and is shown in figure 2.20. The relation was developed by combining elements of the flow relation in figure 2.13, the 21-day low-flow frequency curve in figure 2.14, and the flow-salinity relation of figure 2.19. As an example of the use of the relation in figure 2.20, suppose that it was observed in one year that the maximum intrusion of the saltwater front was 18 miles upstream from the U.S. Highway 17 bridge in Wilmington. According to figure 2.20, we would interpret that the saltwater front would reach this far upstream, or farther, only once every 20 years, on the average.

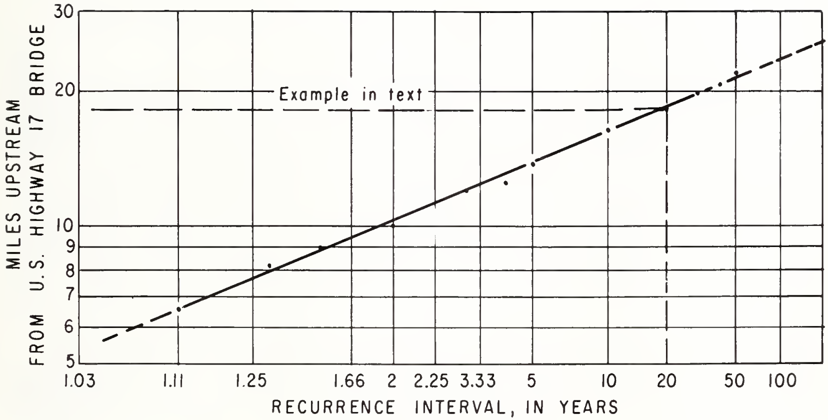


Figure 2.20.--Frequency of intrusion of 200 mg/L chloride for various locations in the Northeast Cape Fear River estuary.

CHAPTER 3

HYDROLOGY OF THE PAMLICO SOUND ESTUARINE SYSTEM

For purposes of the report, the Pamlico Sound estuarine system (plate 1) includes Pamlico Sound, the Neuse-Trent and Tar-Pamlico river systems, and all other estuarine waters tributary to it. Technically, this includes Albemarle Sound and its associated estuarine waters to the north, but because of its large size and relatively minor degree of interaction with Pamlico Sound, the Albemarle Sound estuarine system is considered separately in this report. Core Sound to the south drains partially to Pamlico Sound, but it is not identified with the Pamlico Sound system for present purposes.

The Pamlico Sound will be discussed first because the hydrology of the estuaries opening into it is inextricably related to the hydrology of the sound. Pamlico Sound is connected with the ocean through several relatively small openings in the Outer Banks, primarily Ocracoke, Hatteras, and Oregon Inlets. This limited access, in combination with the broad expanse of the sound, results in ocean tides being dampened to less than 0.2 foot, except near the inlets (Roelof and Bumpus, 1953). However, tidal ranges in the estuaries emptying into Pamlico Sound may be as much as a foot in some locations, due to funnelling effects.

A second feature of the Pamlico Sound system is that, on a short-term basis, wind driven currents are often dominant in both the sound and adjoining estuaries. The large size of Pamlico Sound allows ample opportunity for wind setup over long fetches. Within the estuaries, the velocity of wind-driven currents may be increased because of funneling effects. A second factor which contributes to the relative importance of wind-driven currents in the system is that velocities due to fresh-water inflow are low. Pamlico Sound and its estuaries are drowned river valleys. Consequently, the river channels are oversized for the amount of water they now carry, resulting in low velocities due to freshwater inflow.

In the long term, however, freshwater inflow is more important than wind in affecting net flow because the effects of winds blowing from various directions tend to cancel each other over time. This is true throughout the Pamlico Sound estuarine system.

The data and information on which these discussions are based are from various sources. Plate 1 shows the location of key flow and water-quality data-collection stations operated by the Geological Survey within the Pamlico Sound system. These stations were used to help define freshwater inflow, freshwater quality, and salinity characteristics of the Pamlico Sound system. In addition to data from these sites, the Geological Survey has conducted a number of specific conductance surveys to determine the extent of saltwater intrusion, most notably six surveys

of the Tar-Pamlico and Neuse-Trent systems made between September 14, 1954, and June 1, 1955. In addition to the Geological Survey data, information acquired by the National Oceanic and Atmospheric Administration, the Office of Sea Grant of the National Science Foundation, the University of North Carolina, North Carolina State University, East Carolina University, and Woods Hole Oceanographic Institution was utilized in this study.

Pamlico Sound

Pamlico Sound (plate 1) covers an area of about 2,060 mi^2, bounded on the west by the mainland and on the east by the Outer Banks. It is the largest sound formed behind the barrier beaches along the Atlantic Coast of the United States. The total volume of water contained in it amounts to about 920 billion cubic feet, or about 21 million acre-feet. In contrast to its great area, the average depth is only about 16 feet, and the maximum depth is only 24 feet.

Pamlico Sound is an important commercial and sport fishery, and extensive shallow areas and salt marshes along its fringes serve as nurseries for a variety of commercially and recreationally important marine species, including shrimp, oysters, clams, scallops, blue crabs, spot, striped bass, croaker, and flounder.

Pamlico Sound also is an important link in the Atlantic Intracoastal Waterway. Water-related problems in Pamlico Sound include occasional fish kills due to anoxic conditions, contamination of some clam and oyster producing areas, property damage due to hurricane surge, too-low or too-high salinities in fish nursery areas due to both natural and man-induced causes, shoreline erosion, and sedimentation in shipping channels.

The total area draining directly into Pamlico Sound is about 12,520 mi^2, including the area of Pamlico Sound. In addition, water from Albemarle Sound and areas tributary to it (total of 18,360 mi^2) enters Pamlico Sound indirectly through the Croatan and Roanoke Sounds. Thus, Pamlico Sound receives drainage from a total area of about 30,880 mi^2. The average freshwater inflow to Pamlico Sound from this area is about 32,000 ft^3/s. At this rate, it would take about 11 months for the flow volume to equal the volume of the sound. The average inflow value accounts for precipitation on and evaporation from the sounds and wide open-water areas of the various estuaries. The average monthly inflow to Pamlico Sound ranges from about 55,200 ft^3/s in February to about 21,000 ft^3/s in June.

As discussed by Folger (1972), Bluff Shoal (fig. 3.1) divides Pamlico Sound into two broad basins. Bottom topography in the northern area dips smoothly toward the center to the maximum depth of approximately 24 feet. In the southern part, shoals project from the western

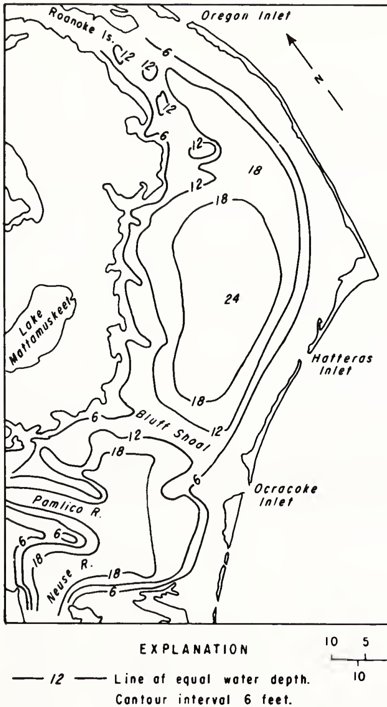


Figure 3.1.--Depth of Pamlico Sound (from Pickett, 1965).

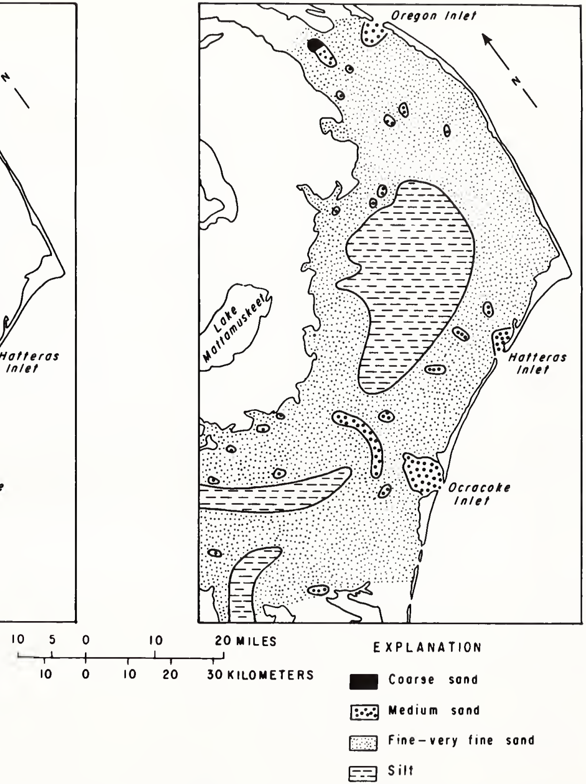


Figure 3.2.--Texture of Bottom sediments in Pamlico Sound (from Folger, 1972, after Pickett, 1965).

shore well into the sound. A tidal delta extends into the sound from Ocracoke Inlet.

Folger notes that fine sand (fig. 3.2) covers most of the bottom, with silt present primarily in the deep areas of the northern basin and in the channels extending into the sound from the mouths of the Neuse and Pamlico rivers. Medium sand covers most shoals and extends soundward from inlets as tidal-channel deltas and from the barrier islands as washover fans.

There is a general increase in oxidizable organic matter and organic carbon in the bottom sediments (fig. 3.3) toward the center of the northern part of the sound and toward the axes of the Neuse and Pamlico River channels where, according to Folger, the finer sediment is concentrated. Most of the organic material is apparently due to indigenous biological activity, although he notes that some peat evidently underlies a thin veneer of sand at the southern end of the sound.

The highest concentrations of calcium carbonate (fig. 3.4) in the bottom sediments are associated with the fine sediments in the northern basin and near the river mouths, and with the medium sands of tidal channel deltas at inlets. The calcium carbonate in these areas is mostly shell detritus.

Water Budget and Flow

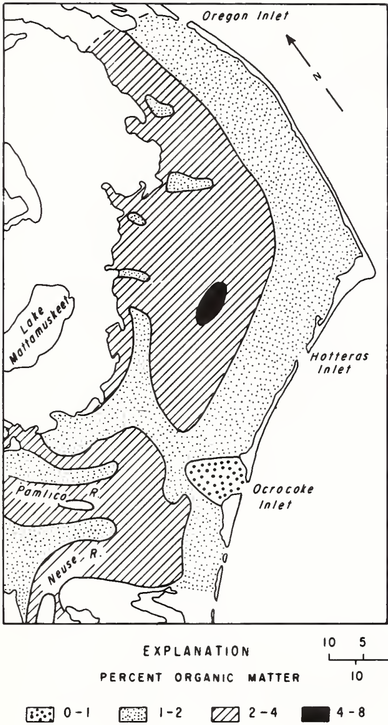
The net freshwater inflow to Pamlico Sound may be determined by a simple accounting of freshwater according to the equation:

$$P + I_\ell - E = I_n \qquad \text{Equation (3.1)}$$

where P is precipitation on the sound, I_ℓ is freshwater inflow from land drainage, E is evaporation from the sound, and I_n is net freshwater inflow to the sound (change in storage in the sound is assumed to be zero). Monthly freshwater budgets were calculated for Pamlico Sound utilizing equation 3.1 and these are shown in table 3.1.

The major freshwater flow contributors to Pamlico Sound are the Neuse-Trent River system (average flow--6,100 ft^3/s from 5,598 mi^2), the Tar-Pamlico River system (average flow--5,400 ft^3/s from 4,300 mi^2). Indirectly, two other major rivers, the Roanoke (average flow--8,900 ft^3/s from 9,666 mi^2) and the Chowan (average flow--4,600 ft^3/s from 4,943 mi^2) drain into Pamlico Sound through Albemarle Sound. The monthly values for these rivers and other contributing areas were determined on the basis of discharge records at gaged locations, adjusted for ungaged areas.

Precipitation values for Pamlico Sound and adjacent open water areas (2,064 mi^2) were determined by averaging National Weather Service



10 5 0 10 20 MILES

10 0 10 20 30 KILOMETERS

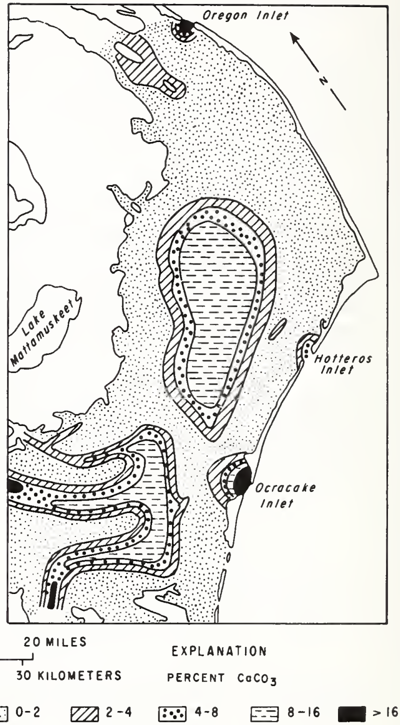


Figure 3.3.--Oxidizable organic matter and organic carbon content of bottom sediment in Pamlico Sound. Oxidizable organic matter data are from Pickett (1965); organic carbon data are from Hathaway (1971).

Figure 3.4.--Calcium carbonate content of bottom sediments in Pamlico Sound (from Pickett, 1965).

Table 3.1.--Monthly and annual gross water budget for Pamlico Sound

Element of Gross water budget	Drainage area in square miles	Average monthly and annual values, in cubic feet per second												
		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average[1/] annual
Precipitation on Pamlico Sound	2,060	6,780	7,930	6,620	5,380	6,590	9,340	12,600	12,100	10,800	6,710	7,080	7,040	8,250
Evaporation from Pamlico Sound	2,060	2,330	3,310	4,900	7,530	8,590	9,320	10,000	7,680	6,110	4,080	3,000	1,990	5,740
Freshwater inflow to Pamlico Sound from land areas tributary to Pamlico Sound	10,460	17,000	21,600	19,100	13,200	11,300	6,220	8,940	10,900	8,530	7,900	8,240	11,100	12,000
Inflow from Albemarle Sound to Pamlico Sound	18,360	22,800	28,300	25,000	21,300	15,500	12,200	14,200	14,700	13,100	10,700	13,300	15,600	17,200
Net inflow to Pamlico Sound (or outflow to the ocean)	30,880	44,200	54,500	45,800	32,400	24,800	18,400	25,700	30,000	25,300	21,200	26,600	31,800	31,700

1/ Rounded.

station records at New Bern, New Holland, and Cape Hatteras. Precipitation on Albemarle Sound and adjacent open-water areas (934 mi^2) was determined from monthly average values from National Weather Service stations at Elizabeth City, Manteo, and Plymouth. Evaporation values were derived for all major open water areas by applying a coefficient of 0.7 to monthly values of the Maysville pan evaporation station of the National Weather Service. Precipitation and evaporation values for Albemarle Sound, though not shown in table 3.1, are reflected in the inflow values from Albemarle Sound.

It is interesting to note from table 3.1 that minimum net inflows to Pamlico Sound do not clearly occur in September, October, and November, as is the case with many natural streams in North Carolina. Actually, minimum net inflows seem to occur in June, when evaporation rates are the greatest.

As is often the case, extreme and unusual events are of greater interest than normal events. It is useful to speculate on what net inflows would be, say, in a month with little or no rainfall occurring during the low-flow period of June-October. In such a situation, freshwater inflow from land drainage would be minimal (say at the 30-day, 10-year minimum flow range) and evaporation would be, if anything, somewhat greater than normal for such a month because incident solar radiation would be greater due to lessened cloud cover. Figure 3.5 shows low-flow frequency curves for 7- and 30-day periods for all inflow due to contributions from land areas draining directly or indirectly into Pamlico Sound. The minimum 30-consecutive day 10-year discharge derived from it is about 3,000 ft^3/s. If we assume that this inflow occurs in June, when evaporation is at a maximum (about 15,300 ft^3/s for Albemarle Sound, Pamlico Sound, and associated open-water areas), and if we further assume that direct precipitation on the sounds and associated open water areas is zero, then net freshwater inflow to Pamlico Sound, Albemarle Sound, and associated areas from equation 3.1 would be (0 + 3,000 - 15,300) ft^3/s, or -12,300 ft^3/s. In other words, the rate of loss of freshwater from the sounds and associated areas by evaporation would exceed gains from land drainage and precipitation by about 32 billion ft^3. Of course, these evaporative losses would be made up by sea water entering Pamlico Sound through the ocean inlets, thus increasing the salinity of the Sound.

High flow periods are also of great interest because the greater part of annual flow volumes occur during relatively short time periods and this is when most of the flushing of pollutants and saline water takes place. By inspection of Table 3.1, it is seen that the highest inflows generally occur from January-April, ranging from an average of 54,500 ft^3/s in February to about 32,400 ft^3/s in April. Figure 3.6 shows high-flow frequency curves of inflow from direct and indirect land drainage into Pamlico Sound for 7- and 30-day periods. As an example to contrast with the minimum 30-consecutive-day 10-year average flow of 3,000 ft^3/s, the maximum 30-consecutive-day 10-year average flow from

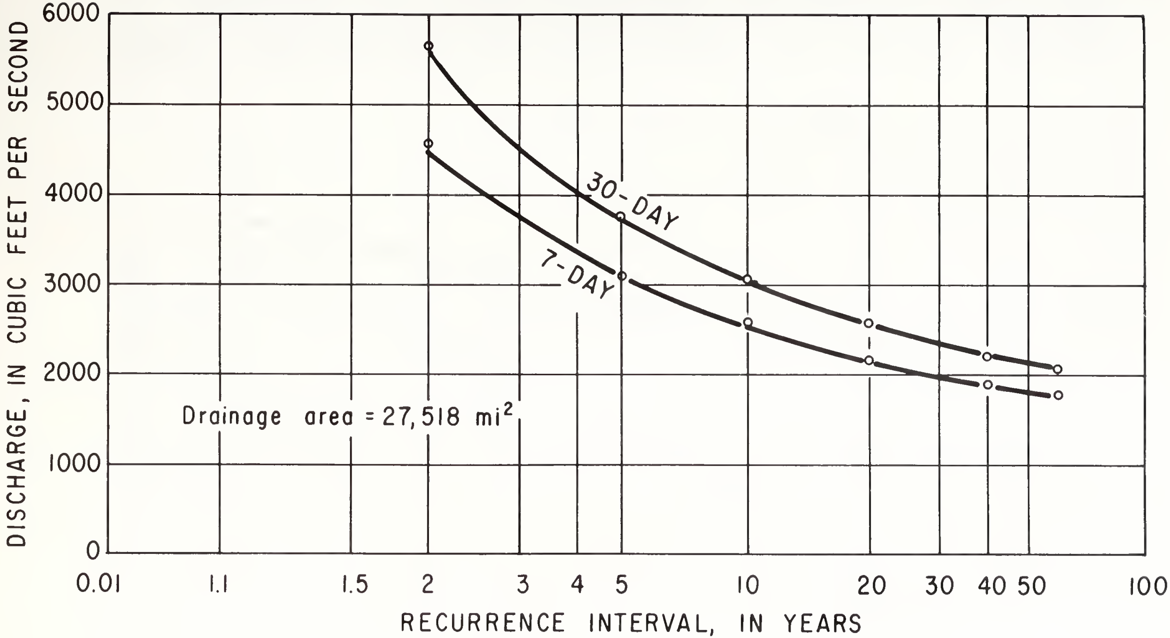


Figure 3.5.--Magnitude and frequency of annual minimum 7 and 30 consecutive-day average inflow to Pamlico Sound from direct and indirect land drainage, not adjusted for precipitation on and evaporation from Pamlico and Albemarle Sounds and associated open-water areas.

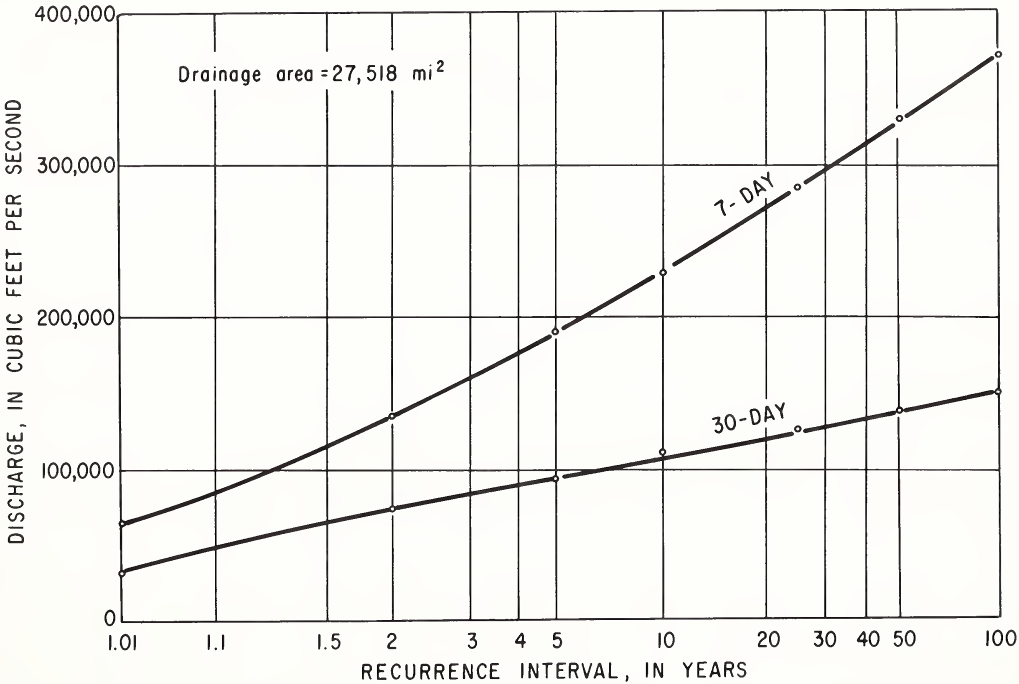


Figure 3.6.--Magnitude and frequency of annual maximum 7 and 30 consecutive-day average inflow to Pamlico Sound from direct and indirect land drainage, not adjusted for precipitation on and evaporation from Pamlico and Albemarle Sounds and associated open-water areas. The total area not adjusted for is 3,362 square miles of the total drainage area of Pamlico Sound of 30,880 square miles.

figure 3.6 is about 106,000 ft^3/s, about 35 times as great. If this inflow were to occur in February, when the excess of precipitation over evaporation is, on average, equivalent to an additional inflow of about 5,200 ft^3/s, then the net inflow (or outflow) would be about 111,000 ft^3/s, or an equivalent volume of about 269 million ft^3 (29 percent of the volume of Pamlico Sound). At this rate, in a period of 14 weeks the water reaching the sound would equal the volume in storage, in contrast to the 11 months needed for average freshwater inflow to reach this volume.

Discharges and resultant velocities due to freshwater flow into and out of Pamlico Sound are of small magnitude and usually overshadowed at any given moment by flows and velocities due to winds and/or tides. However, net flows due to tides and winds tend to approach zero over time, so that long-term average net flows at any point may be ascribed primarily to freshwater inflow. Consequently, flows due to freshwater inflow may have value in studies of long-term net transport of pollutants and nutrients into and out of Pamlico Sound.

An idea of the magnitude of tidal exchange between the ocean and Pamlico Sound may be obtained from table 3.2, which indicates that combined maximum flood or ebb flows through Oregon, Hatteras and Ocracoke Inlets may be on the order of 200,000 ft^3/s, far more than the net outflow of about 32,000 ft^3/s due to freshwater inflow. Although total volumes associated with ebb flows (table 3.2) exceed over time those associated with flood flows, in the case of almost half of the individual measurements in table 3.2, the volumes associated with flood flows exceed those associated with the preceding or following ebbs. It may be that some or even all of these apparent exceedences of individual flood volumes over ebb volumes could be accounted for by measurement error or diurnal inequalities in tides, but just as likely the exceedences were real and caused by easterly winds prevailing during or before the measurements. It is also worthy of note that maximum flow rates occurred during flood tide in the majority of measurements, even in some cases where total ebb volumes exceeded those for floods.

Table 3.3 gives predicted tide ranges and maximum currents for several locations at or near the inlets. The locations of these inlets are shown in plate 1. The predicted mean tidal ranges at the inlets are all similar, from 1.9 to 2.0 feet, though they are less than in the adjacent ocean, where predicted tide ranges vary from 3.2 feet at Kitty Hawk to 3.4 feet at Hatteras. It is interesting to note from comparison of the Ocracoke Inlet and Ocracoke stations how quickly tides damp out away from the inlets. At Ocracoke Inlet, the mean predicted tidal range is 1.9 feet, while at Ocracoke, located in Pamlico Sound only about 4.8 miles northeast of the inlet station, mean ranges are nearly halved, to 1.0 foot.

Table 3.2.--Tidal flow and related data for Oregon, Hatteras and Ocracoke Inlets. Except for measurements made in April 1950, by Roelofs and Bumpus and on June 28, 1973, by Singer and Knowles, the measurements are from records of the U. S. Army Corps of Engineers

Date	Cross section (ft^2) at mlw	Maximum rate of flow (ft^3/s)		Total Flow (acre-ft.)	
		Flood	ebb	Flood	Ebb
		Oregon Inlet			
Sept. 9, 1931	39,000	134,100	88,200	47,800	37,400
Aug. 31, 1932		129,100	102,700	42,700	40,100
Oct. 11, 1932		126,500	127,300	34,900	57,200
Aug. 24, 1937	44,400	180,000	142,000	63,500	55,900
Aug. 14, 1939	56,000	152,000	141,000	37,800	71,500
Apr. 23, 1950	28,000		90,000		38,200
Sept.27, 1965	66,800	292,000	145,800	98,200	54,200
June 28, 1973	68,800	171,000	146,000		
		Hatteras Inlet			
Apr. 25, 1950				52,700	
		Ocracoke Inlet			
Apr. 27, 1950	82,800			45,400	122,000
May 25, 1958	107,500	285,000		78,400	
May 25, 1958	96,100		273,000		104,000
Oct. 14, 1962	94,100	329,000		125,000	
Oct. 14, 1962	74,400		344,000		129,000

Of course, tide predictions are made on the basis of an analysis of predictable mutual gravitation forces of the sun, moon, and earth and actual tide heights and currents in Pamlico Sound often differ from predictions, primarily because of the unpredictable effects of winds. Detailed consideration of the complex effects of winds on circulation in Pamlico Sound is beyond the scope of this report, but several reports, including Singer and Knowles (1975) and Knowles (1975) discuss the effects of winds and tides on circulation at several locations in and near Pamlico Sound.

Table 3.3.--Predicted tide ranges and maximum currents for locations at or near inlets to Pamlico Sound. From National Ocean Survey Tidal Current Tables and Tide Tables for 1977.

	Location		Tidal ranges in feet		Average maximum currents in feet per second	
	Lat.	Long.	mean	spring	Average flood velocity	Average ebb velocity
Oregon Inlet	35°46'	75°32'	2.0	2.4		
Hatteras Inlet	35°12'	75°44'	2.0	2.4	3.6	3.4
Ocracoke Inlet	35°04'	76°01'	1.9	2.3	2.9	4.0
Ocracoke, Ocracoke Inlet	35°07'	75°59'	1.0	1.2		

Water Levels

The greatest water level fluctuations in Pamlico Sound occur during hurricanes, when land areas 10 to 15 feet above mean sea level are sometimes innundated, causing great damage to buildings and croplands adjacent to the sound. Figure 3.7 shows water level configurations during Hurricane Donna at 0200 and 0500 hours on September 12, 1960. These contours were sketched by the U.S. Army Corps of Engineers from tide gage records and appeared in the 1961 publication "Report on the tropical hurricane of September 1960 (Donna)." They illustrate not only the wide variations in stage which may exist from place to place at a given time, but also the great fluctuations which may occur at a given place in a relatively short period of time during hurricanes. It is important to note that the datum for figure 3.7 is 4.0 feet below mean sea level; thus, for example, a water level contour of 1.0 foot in figure 3.7 is actually 3.0 feet below mean sea level.

An important tool for gaging potential flood losses from winds is knowledge of the frequency of flooding. The following three paragraphs on this subject are almost a direct quote from Wilder and others (1978, p. 58-59). Only the illustration numbers have been changed:

"Prediction of the frequency with which a given locality is likely to be flooded with water from the estuaries or sounds is inexact because of the almost infinite number of possible combinations of wind direction and velocity, shoreline configuration, fetch, and the amount of vegetation and man-made structures that might impede free advancement of a wave. Some idea of the severity of the problem can be obtained from

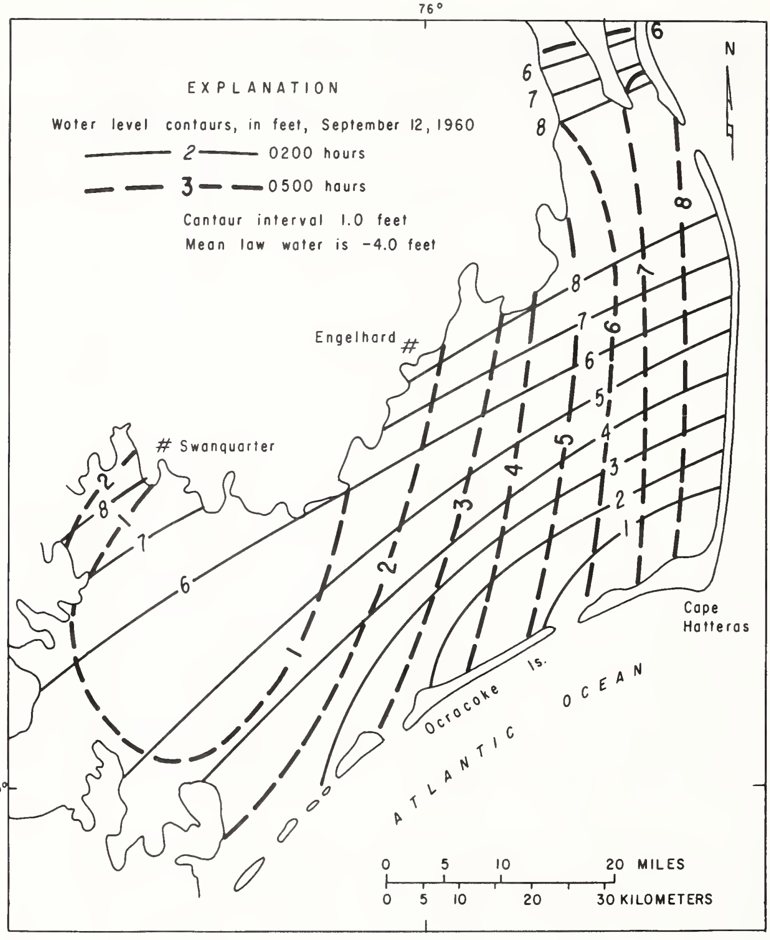


Figure 3.7.--Estimated water levels in Pamlico Sound at 0200 and 0500 hours on September 12, 1960, during Hurricane Donna. From Amein and Airan (1976), after U.S. Army Corps of Engineers (1961).

figure 3.8, on which are delineated approximate boundaries of wind-tide floods likely to be equalled or exceeded 50 percent of the years and 1 percent of the years. By "exceeded" we mean that inundation of an area at least as great as that shown is likely every other year on the average at the 50 percent probability, and once every hundred years on the average at 1 percent probability. These are average frequencies over long periods of time, and no specific time interval between two consecutive events is implied... However, all of the area with an equal chance of being flooded at a given frequency will seldom, if ever, be flooded by the same storm. For example, strong southerly winds cause inundation along northern shorelines of a body of water, but might actually lower water levels along the southern shorelines.

"It is important also to qualify the accuracy of figure 3.8. The boundary outlining the area inundated by a flood with a 1 percent chance of exceedance was transferred directly from flood-prone area maps available from the U.S. Geological Survey. The lines in figure 3.8 are general and are not as detailed as those appearing on the large-scale flood-prone maps. These small-scale illustrations were prepared only to point out the potential flood problem. If more accurate data are desired, the large-scale flood-prone maps prepared by the Geological Survey and flood-plain information studies completed by the U.S. Army Corps of Engineers should be used. Generally the flood with a 50 percent chance of exceedance was sketched on the large scale floodprone area maps using a flood stage from 2.5 to 3.5 ft below the flood out lined as having a 1 percent change of exceedance and then transferred directly to the smaller scale maps of figure 3.8.

"Because most of the areas adjacent to the shorelines presently contain dense vegetation or manmade structures, these sources of tidal-flooding information, all of which consider only wave height and land elevation, may tend to overestimate the extent of inundation."

Water Quality

Marshall (1951) pointed out the lack of data on water chemistry other than salinity in the open parts of Pamlico Sound and suggested this as an important area of study. His statement remains largely true today, although some valuable data have been and are being collected by various agencies, including the University of North Carolina Institute of Marine Sciences (summarized in Williams and others, 1967) and the North Carolina Department of Natural Resources and Community Development. However, much of these data were collected along the fringes of the Sound, not in the central part. The U.S. Geological Survey has collected chemical data for many years at various locations on rivers tributary to Pamlico Sound. These data will be discussed in later sections, but extrapolation of this information to infer water quality of Pamlico Sound would be very difficult for two primary reasons.

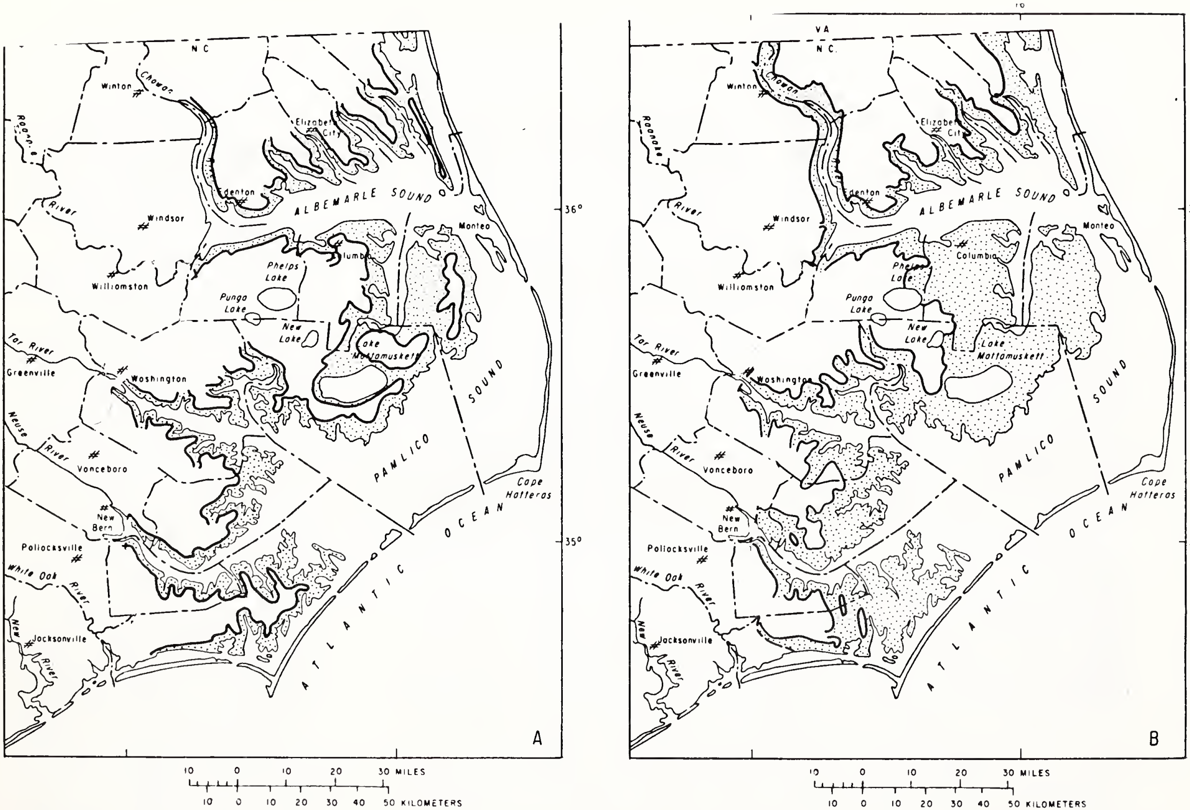


Figure 3.8.--Areas subject to flood inundation caused by wind tides having A, 50 percent chance of being equaled or exceeded in any one year and B, 1 percent chance of being equaled or exceeded in any one year. After Wilder and other, 1978.

First, of course, Pamlico Sound water is everywhere at all times at least partially mixed with ocean water. The second primary reason is that some chemical constituents, such as nitrate (NO_3) and phosphate (PO_4), are non-conservative and continue to interact chemically and biochemically with other substances or organisms in the water as the water moves into Pamlico Sound and, ultimately, into the Atlantic Ocean. The Pamlico River estuary, for example, acts as a trap for phosphate and nitrate during algal blooms, which occur there each late winter or early spring and each summer (Hobbie, 1974, p. 2). The algae trap and utilize phosphorous and nitrogen for growth, then die and settle to the river bottom. Thus, phosphate and nitrate concentrations in the river water may be much decreased by the time the water reaches Pamlico Sound.

Woods (1967), collected data on water quality at several sites in southern Pamlico Sound from June 1963-October 1966 (fig. 3.9). At one-month intervals at each site, vertical salinity and temperature measurements were made at one meter intervals and surface and bottom samples were analyzed for dissolved oxygen, plant pigment concentrations, and total phosphate. In his report, Woods indicated that both phosphorous and nitrogen are often present in high-enough concentrations in western Pamlico Sound to support algal blooms and that availability of nitrogen, rather than phosphorous, seems to be the limiting nutrient determining whether or not algal blooms may occur in Pamlico Sound, if other conditions for blooms are favorable.

Dissolved oxygen concentrations in Pamlico Sound ranged from 4-11 mg/L through the course of Woods' study. The highest values occurred when water was cold and the lowest values when water was warmer. In terms of percent saturation, concentrations seldom went below 50 to 60 percent and during the winter months were normally close to 100 percent. Surface dissolved oxygen in Pamlico Sound varied little from place to place at any one time and vertical differences in the sound were slight, even when total oxygen depletion was noted at some bottom stations upstream in the Pamlico River estuary.

Many observers have noted that water temperatures in Pamlico Sound follow air temperatures closely but with some lag. Highest temperatures typically occur during late June, July and August and lowest temperatures occur during the winter months (fig. 3.10A). Figure 3.10B shows the relation between average surface temperature in the open sound and air temperature recorded by the National Weather Service at Hatteras. The air temperatures used in the graph represent the average of the mean temperatures on the day of water temperature observations and the previous day. This was done to allow for the lag in water temperature. Roelofs and Bumpus found the correlation coefficient between mean water temperature and air temperature to be 0.972, which is highly significant.

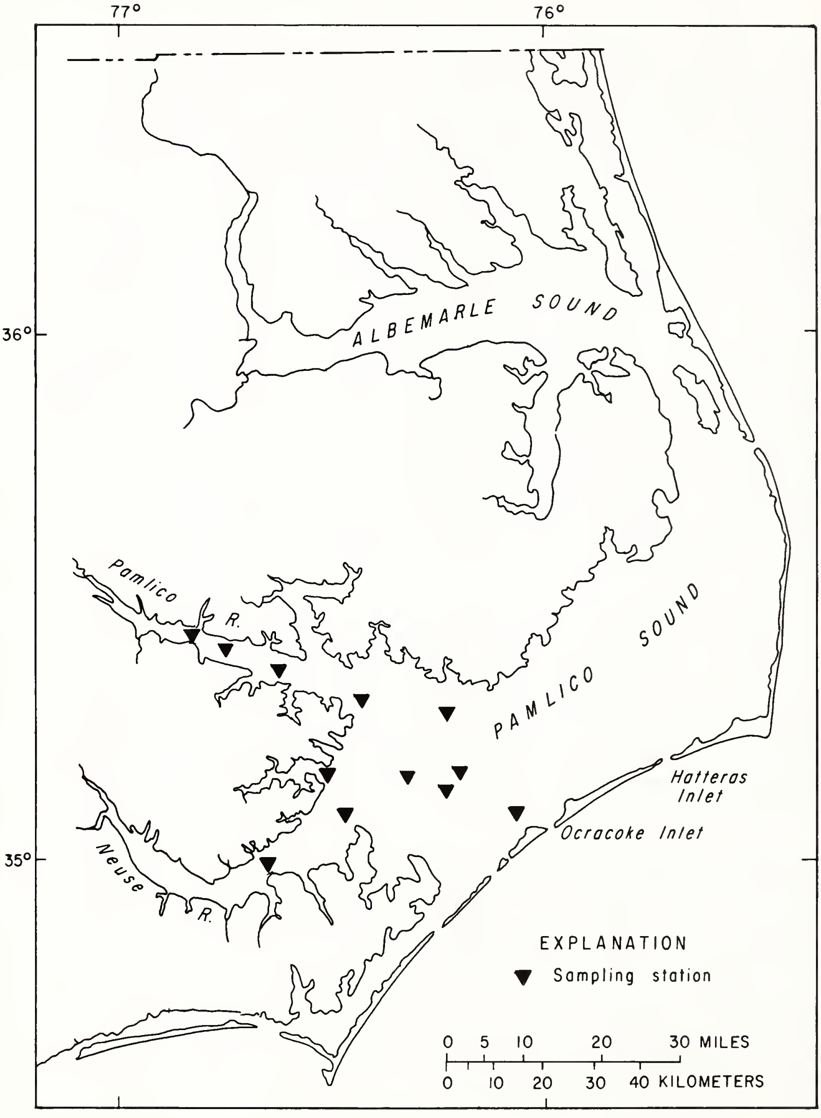


Figure 3.9.--Sampling stations used in Pamlico Sound study by Woods (1967).

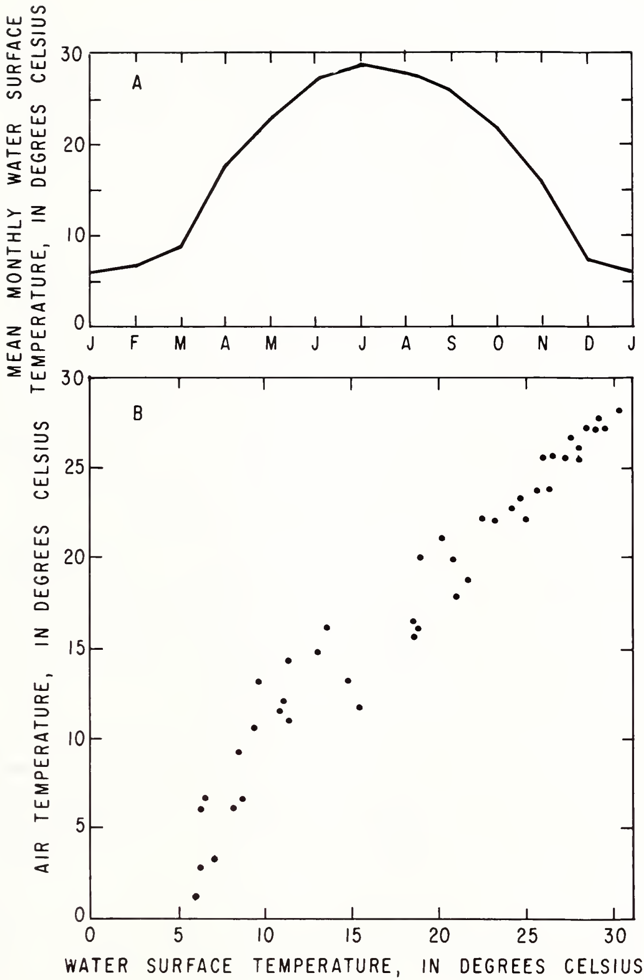


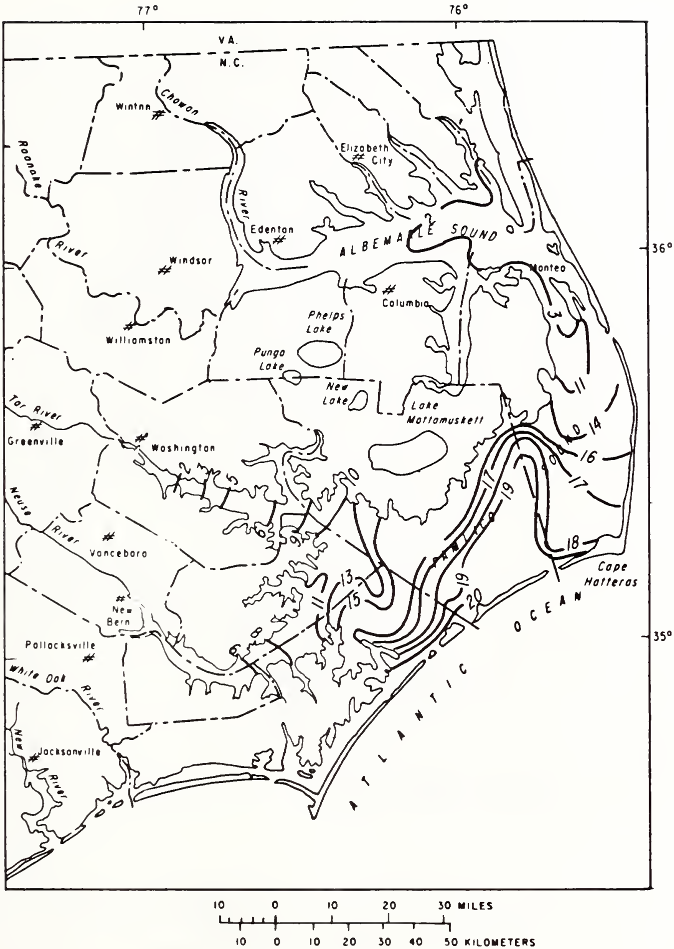
Figure 3.10.--(A). Mean monthly water surface temperature of Pamlico Sound. (B). Relation between water surface temperature of Pamlico Sound and air temperature at Hatteras. Adapted from Roelofs and Bumpus (1953).

Thermal stratification in the open sound is slight year-round; surface to bottom differences rarely exceed 1 or 2°C. Areal differences are likewise small, rarely exceeding 3 or 4°C at any one time. Apparently, winds are effective in promoting vertical mixing throughout the relatively shallow depths of the sound.

Salinity

Figures 3.11 and 3.12 show the average surface salinity of waters of the Pamlico Sound system for the months of April and December, based on salinity data collected between 1948 and 1966 at a number of fixed locations in the system. April, on average, is the month of lowest salinities and December is the month of greatest salinities. The April-December differences are less at the ocean inlets (0-2 grams per kilogram) than they are near the mouths of the major estuaries where the April-December differences may be 4-5 grams per kilogram. The effect of high freshwater inflows during the late winter and spring months from the Albemarle Sound drainage and the Neuse-Trent and Tar-Pamlico river systems may be seen in the way the high-salinity water has been "pushed" further out into Pamlico Sound in April as compared to December. Actually, maximum net outflows occur, on average, not in April but in February, and minimum outflows occur, on average, not in December but in June or October. This lag in salinity response to changing outflows is due to the large volume of Pamlico Sound and the long time required to flush water out of the sound. Thus, the salinity distribution within the sound during any one month is due, not only to flows during that month, but to the flows during the immediately preceding months.

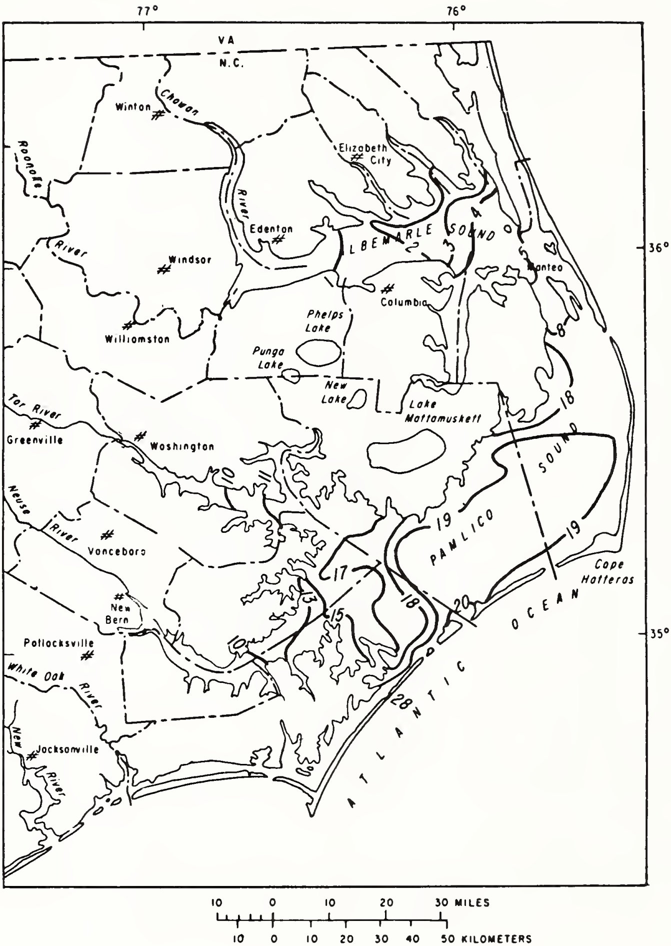
Just as winds are the dominant influence on the short-term circulation of water in Pamlico Sound, they are also the dominant short-term influence on salinity distributions. It has been generally observed that easterly winds cause increasing salinities in the sound and westerly winds cause decreasing salinities. However, with regard to the effects of northerly and southerly winds, there is some confusion. Most observers agree that northerly winds will cause lower salinities in the northern part of Pamlico Sound as fresher water is pushed into this area from Albemarle Sound. They also agree that southerly winds will cause higher salinities in the northern part of Pamlico Sound as highly saline water from Hatteras and Ocracoke inlets is driven northward. It is the effect of northerly and southerly winds in southern Pamlico Sound which has been disputed. Winslow (1889) reported that southerly winds will cause decreasing densities (salinities) in the southern part of Pamlico Sound and Core Sound and northerly winds will cause increasing salinities there. However, Roelofs and Bumpus (1953) observed decreasing salinities in Core Sound during northerly winds as fresher Pamlico Sound water was "blown" into Core Sound. More study is needed to resolve these observational differences, but Whalebone Inlet, now closed, was open during Winslow's 1889 observations, and Drum Inlet, now



EXPLANATION

——19—— SALINITY, IN GRAMS PER KILOGRAM. (Sea water contains about 34.5 grams of dissolved solids per kilogram.) Contour interval variable.

Figure 3.11.--Average surface salinity of water in Pamlico Sound and vicinity for the month of April. Modified from Williams and others (1967).



EXPLANATION

—19— SALINITY, IN GRAMS PER KILOGRAM. (Sea water contains about 34.5 grams of dissolved solids per kilogram.) Contour interval variable.

Figure 3.12.--Average surface salinity of water in Pamlico Sound and vicinity for the month of December. Adapted from Williams and others (1967).

open, was then closed. This would argue for accepting the more recent observations by Roelofs and Bumpus. Also it is probably too simplistic to say that higher salinity waters will always prevail at a given location with winds from a given direction. The wind speed and its duration are also important factors. Winds which have prevailed need also to be considered. For example, reversal in salinity trends may occur at a given location if wind has prevailed in a given direction for more than, say, 24 hours, due to water buildup on one side of the sound creating a return flow situation (Singer and Knowles, 1975).

Salinity stratification in the open sound is usually slight, only 0.50 to 1.0 percent greater at the bottom than at the surface (Woods, 1967). Roelofs and Bumpus (1953) give the average difference in surface and bottom salinities as only 0.66 percent; this small difference they attribute to effective mixing by the winds throughout the shallow open-sound depths. Woods did observe larger open-sound surface-to-bottom salinity increases of as much as 6 percent from the surface to the bottom in 1964 during the spring, summer and fall. Woods thought that this stratification was due to increased freshwater inflows from the Neuse and Pamlico rivers which occurred approximately four to seven weeks prior to the observed stratification in the open sound.

Magnuson (1967) indicated that salinities in parts of natural or man-made channels connecting to the inlets may be appreciably greater than salinities in adjacent shallower areas. However, this is partly speculative and needs better confirmation from data.

The distribution of many aquatic organisms in Pamlico Sound and its estuaries and salt-marsh fringes is influenced greatly by salinity patterns. Some aquatic organisms can tolerate wide salinity ranges from almost fresh to almost sea water (Thayer, 1975, p. 64). Others can live and reproduce only within narrow ranges; still others require different salinity conditions at different stages of their life cycles. Thus, any modifications by man in the amount and annual distribution of freshwater inflow or in alteration of salinity patterns will exert some control on the plant and animal populations in Pamlico Sound and adjoining areas. The effects of upstream reservoirs (such as the proposed Falls of the Neuse reservoir), the effects of land clearing on freshwater runoff (such as is currently taking place on the Albemarle-Pamlico peninsula), and the effects of creating new ocean inlets and navigation channels should all be carefully evaluated with regard to the above salinity considerations.

The Neuse-Trent River System

The Neuse River (plate 1) heads in Durham County, North Carolina, at the confluence of the Eno and Flat Rivers in the hilly Piedmont Province. The river flows southeast, enters the Coastal Plain near

Smithfield, and empties into Pamlico Sound at Maw Point. The total length of the main stem of the river is about 250 miles, and its drainage area is approximately 5,600 mi^2, which is about 11 percent of the total area of North Carolina. The average annual precipitation ranges from near 45 inches in Durham County to about 54 inches at New Bern. The mean annual flow, measured at the most downstream gaging station, at Kinston (station 02089500 on plate 1), is about 2,900 ft^3/s for a drainage area of 2,690 mi^2.

The Trent River heads in Lenoir County, North Carolina, and flows almost due east to its confluence with the Neuse River at New Bern. This juncture is about 38 miles upstream from the mouth of the Neuse River at Maw Point on Pamlico Sound. The Trent drainage area of 516 mi^2 is included in the 5,600 mi^2 drainage area of the Neuse River. The total length of the Trent River is about 80 miles and the mean annual flow at the gaging station at Trenton (station 02092500 in plate 1) is about 200 ft^3/s for a drainage area of 168 mi^2.

The estimated average annual discharge into Pamlico Sound at the mouth of the Neuse River (Plate 1) from the entire 5,600 mi^2 drainage area of the Neuse-Trent river system is about 6,100 ft^3/s. The estimated average monthly discharges at the mouth, in cubic feet per second, are as follows:

Jan. - 8,400	Apr. - 7,700	July - 5,000	Oct. - 3,800
Feb. - 11,000	May - 4,200	Aug. - 5,300	Nov. - 3,800
Mar. - 10,000	June - 3,400	Sept. - 5,000	Dec. - 5,800

The upstream limit of tide effects in the Neuse and Trent Rivers has not been well established, but is thought to be near Fort Barnwell on the Neuse River (about 65 miles upstream from the mouth at Maw Point); on the Trent River the upstream limit of tide effects is thought to be about halfway between Pollocksville and Trenton, or about 35 miles upstream from its mouth at New Bern (about 73 miles upstream from the mouth of the Neuse River).

The Neuse River estuary varies from 6.3 miles wide and an average depth of 17 feet at its mouth near Maw Point to a width of about 0.9 mile and an average depth of about 8 feet at New Bern. From New Bern to the head of tide near Fort Barnwell, the estuary narrows considerably and maximum depths are at least 3 feet in any cross section.

The Trent River estuary varies from 0.3 mile wide and about 10 feet deep at the mouth at New Bern to about 50 feet wide and 4 feet deep at the head of tide near Pollocksville.

Effects of Wind on Water Levels and Specific Conductance

Water levels in the lower parts of the Neuse River and Trent River estuaries are primarily controlled by the direction and magnitude of the surface winds on Pamlico Sound. Because of the dampening effect of Pamlico Sound, tidal ranges are less than a foot at New Bern. Variations in water levels due to freshwater inflow are also small because the surface areas of the lower parts of these estuaries are large relative to freshwater inflow.

Figure 3.13 is a wind diagram for resolving a given wind to the directional component which is effective in causing a change in water level at New Bern. The values on the circle are based on the cosine of the angle between the actual direction of the wind and the direction which causes the maximum effect. Winds blowing in the direction of the lower channel axis of the Neuse River (the lower 15 miles) have the greatest effect on the level of water in the estuary. This axis of maximum wind effect forms an angle of 60° with true north. Thus, a wind blowing from due north (cos 60° = 0.5) is only half as effective in producing high water levels at New Bern as a wind that blows from 60° east.

Figure 3.14 is a curve that relates the wind component to the change in water level at New Bern. The curve shown was developed from Geological Survey water level records of the Neuse River at New Bern and wind speed and direction records from the National Weather Service station at New Bern. This relation might be used as a rough predictor of potential hurricane flooding and in assigning flood risks to streambank areas. To predict water level changes in the Neuse estuary at New Bern resulting from winds acting on Pamlico Sound, determine the direction of the wind, then multiply its velocity by the cosine of the angle formed between the actual wind direction and the direction of maximum effect, obtained from figure 3.13. The result is the wind velocity component. Then enter figure 3.14 with the wind velocity component and read the change in water level on the abscissa.

Example: a 30 mi/hr wind from the east

From figure 3.13, cosine of angle between actual wind direction and direction of maximum effect (30) = 0.87.

Therefore, 0.87 x 30 = 26 mi/hr.

And from figure 3.14, water level change = 4.6 ft rise.

The highest recorded water levels at New Bern have been caused by a combination of hurricane winds, the associated low barometric pressure, and intense short-term rainfall. Hurricane Ione (September 19,1955) passed about 15 miles east of New Bern on a northerly course and caused

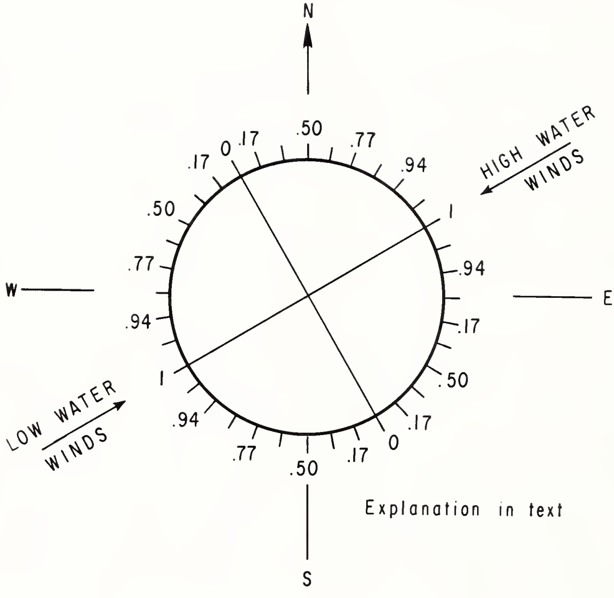


Figure 3.13.--Wind diagram for the Neuse River estuary at New Bern.

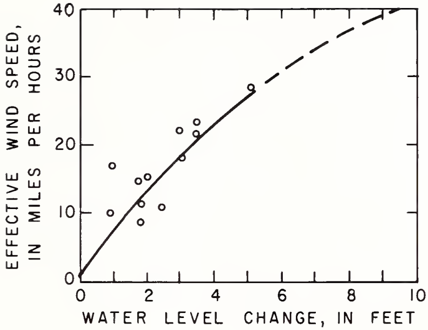


Figure 3.14.--Change in water level of the Neuse River estuary at New Bern due to wind as recorded at New Bern airport.

water levels to rise 10.6 feet above msl for a short period. The maximum wind recorded near New Bern then was 107 mi/hr, the lowest barometric pressure was 27.7 inches, and over 13 inches of rain were recorded at New Bern. At least four other hurricanes since 1913 have caused water levels to exceed seven feet above msl.

An example of the general effect of wind on water levels and saltwater intrusion at New Bern is shown in figure 3.15. During most of the period from January 22 through 29, 1965, winds were blowing generally from the south and west, the wind directions that tend to lower the water level of the estuary. Salty water from Pamlico Sound, which had previously intruded up the estuary beyond New Bern, was flushed downstream, as indicated by the drastic decline in specific conductivity on January 23. The conductivity remained low until January 28 when a short-lived decline in wind speed permitted salty water to again intrude past New Bern. The salty water was again flushed on January 29 when southeast winds arose, but the salt water was immediately forced back up the estuary when the wind shifted to the northeast and high-water winds blew on January 30.

Water Quality

The chemical quality of the freshwater entering the estuaries from upstream is, where not contaminated, of acceptable quality for public and industrial use with a minimum of treatment. Table 3.4 shows the maximum, minimum and average of dissolved mineral constituents from a

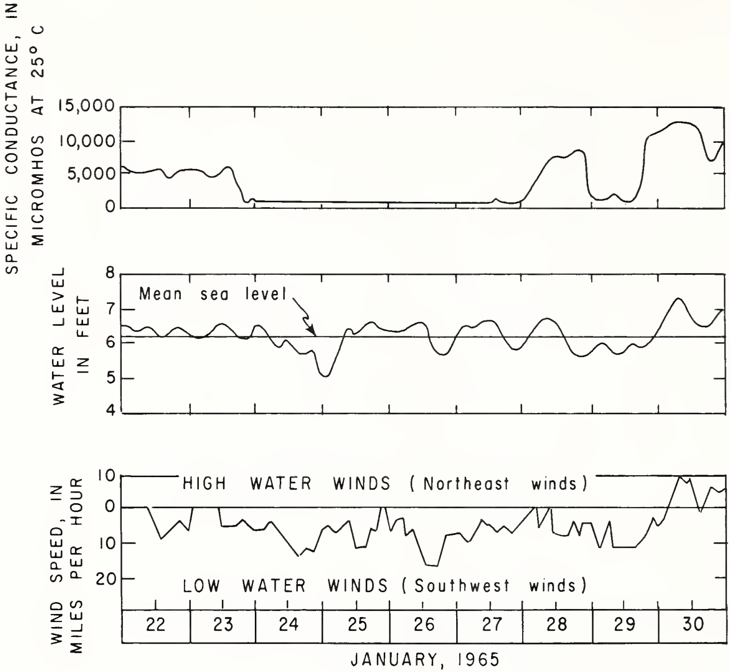


Figure 3.15.--Effect of wind on water levels and bottom specific conductance in the Neuse River estuary at New Bern, January 22-30, 1965. Datum of water level gage is -6.15 ft MSL.

site on each river upstream from any saltwater contamination. Generally, maximum concentrations reflect the quality of the ground water entering each river and minimum concentrations are more reflective of surface runoff. The main difference in water quality between the two rivers is that concentrations of most dissolved constituents for the Neuse River average significantly more than those for the Trent River. The major exceptions are bicarbonate (HCO_3) and calcium (Ca) which average higher for the Trent River. The higher concentrations in the Trent River are the result of significant ground-water inflow from the Castle Hayne Limestone. High color and iron are sometimes a problem with water in both estuaries.

Some reaches of the Neuse River estuary occasionally undergo oxygen depletion due to algal blooms which may utilize all available oxygen, resulting in fish kills and the destruction of most bottom-dwelling

Table 3.4.--Summary of chemical analyses of water samples collected at key stations in the Neuse-Trent river system. Chemical constituents are in milligrams per liter, except specific conductance, pH, and color. (Adapted from Wilder and Slack, 1971a).

Station number	Station name	Drainage area in mi^2	Period of sampling	Sampling frequency	Extremes and averages	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)		Nitrate (NO_3)	Dissolved solids Residue	Hardness as $CaCO_3$ Calcium magnesium	Hardness as $CaCO_3$ Non-carbonate	Specific conductance (Micromhos at 25°C)	pH	Color units
02091814	Neuse River near Ft. Barnwell	about 3,900	Oct. 1954 to Sept. 1969	daily	Max	14	.89	65	4.0	25	5.7	204	17	53	.3		20	186	171	16	673	8.4	150
					Min	4.0	.00	3.0	.2	3.8	.5	4	3.2	3.4	.0		.8	42	11	0	39	5.0	8
					Avg	10	.19	5.5	1.5	7.4	1.8	20	6.9	8.7	.1		2.2	65	20	4	84	...	50
02092500	Trent River near Trenton	168	Oct. 1951 to Aug. 1967	daily	Max	11	.77	42	3.2	11	2.3	126	51	12	.6		7.4	153	117	54	257	8.0	240
					Min	1.2	.00	4.7	.3	1.6	.2	10	2.1	2.0	.0		.0	40	15	1	31	6.1	14
					Avg	6.3	.18	17	1.4	4.3	.7	43	9.6	7.0	.1		1.4	90	54	12	118	...	94

organisms. The role of nutrients in promoting these destructive algal blooms in the Neuse estuary is discussed by Hobbie (1975).

The temperature of the water in the estuaries is directly related to the seasons (fig. 3.16). Maximum temperatures usually occur in July and the minimums in January. Only small temperature differences are detectable laterally in any cross section and seldom does more than one degree Celsius temperature difference exists from the surface to the bottom.

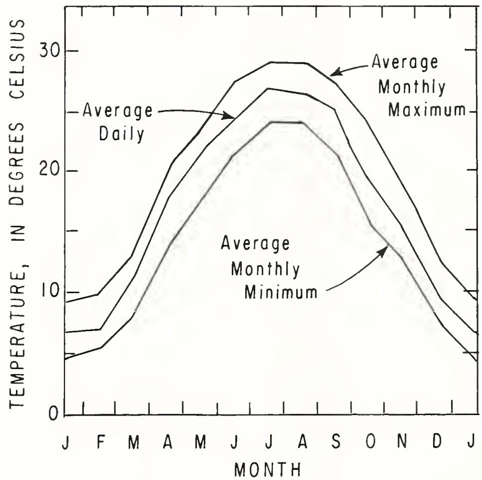


Figure 3.16.--Range of water temperatures in Neuse River estuary at New Bern from October 1963 through August 1967.

Spatial Variations in Salinity

Although water in Pamlico Sound is usually well mixed by wind and currents and is almost always uniform in salinity from the surface to the bottom, salinity stratification often occurs near the mouth of the Neuse River estuary during and following periods of sustained high freshwater inflow. This stratification is the result of the lighter freshwater overriding the more dense saltwater. Stratificiation is even

more common further upstream in the estuarine portions of the Neuse and Trent rivers and at times may be quite pronounced. Samples have been collected where the surface-to-bottom salinity ratio approached 0.01. Usually, however, this ratio is not less than 0.8.

Lateral salinity variations within a cross section of the wide portion of the estuary are also quite common. The salinity is usually higher on the left bank of the estuary (in the sense of facing downstream), a phenomenon attributed to the Coriolis force, as discussed in the GENERAL HYDROLOGY section. In the northern hemisphere, this force tends to deflect a mass to the right of its direction of motion. Thus, the salty water intruding up the estuary tends toward the left bank and the fresh water flowing down the estuary tends toward the right bank. Figure 3.17 shows this effect for the Neuse River as observed during a survey of surface specific conductance on August 13, 1967. The specific conductance of the water at the left bank was more than 4,000 µmhos while on the right bank, directly across the channel, it was as low as 1,000 µmhos. This phenomenon has also been observed in the wide sections of other North Carolina estuaries.

Field specific conductivity surveys have shown that, for the narrow reaches of the Neuse River and Trent River estuaries, relations between the specific conductance at one location and the specific conductance at other locations either upstream or downstream are fairly constant. Figure 3.18 shows such relations for the Neuse River estuary (valid upstream from the U.S. 17 bridge at New Bern) and the Trent River estuary (valid throughout its length). The relation for the Neuse upstream from New Bern is based on ten specific conductance surveys made by the Geological Survey between September 1954 and September 1968. The relation for the Trent River estuary is based on nine surveys made during the same period. As may be deduced from figure 3.18, the change in specific conductance for a given distance is greater for the Neuse River estuary (874 µmhos/mi) than for the Trent River estuary (704 µmhos/mi). This is primarily due to the greater volume of freshwater flowing down the Neuse River that resists the upstream intrusion of saltwater from Pamlico Sound. On the average, about 4,200 ft^3/s of freshwater flows into the Neuse River estuary at Fort Barnwell compared to an average of only about 450 ft^3/s at Pollocksville on the Trent River estuary.

Frequency of Saltwater Intrusion

Information on the frequency of saltwater intrusion at various locations in the Neuse and Trent River estuaries may have application in siting intakes for water supplies. Although no single water-quality criterion may be given, it was noted earlier that water with a chloride concentration of 250 mg/L is unsuitable for public supplies and water containing more than 500 mg/L is unsuitable for a variety of industrial uses.

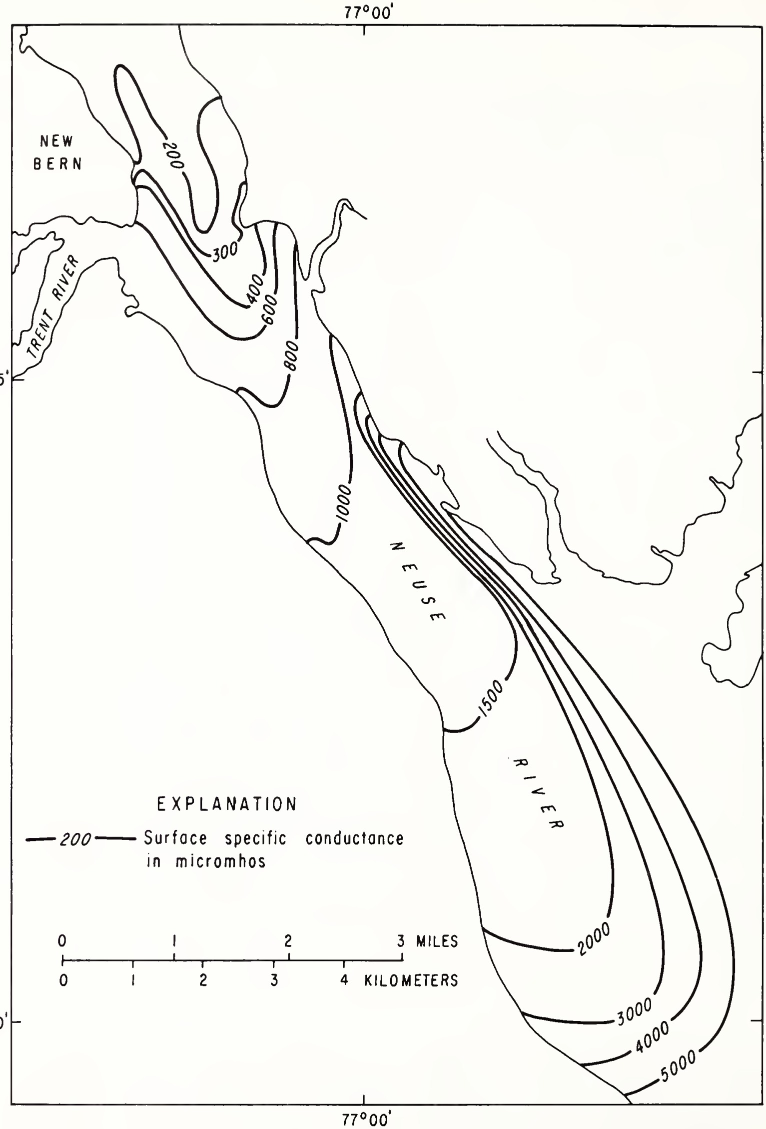


Figure 3.17.--Lines of equal specific conductance for the Neuse River estuary, August 13, 1967.

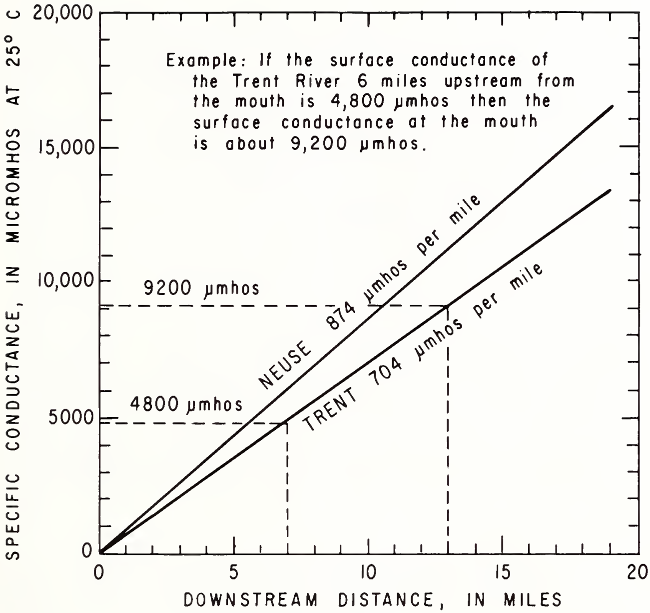


Figure 3.18.--Change in surface specific conductance with upstream and downstream distance in the Neuse and Trent estuaries.

The U.S. Geological Survey collected water samples daily from the surface and bottom of the Neuse at the U.S. 17 bridge in New Bern (station 02092162 on plate 1) from 1957 through 1967. The specific conductance of these daily samples was checked against the record of a monitor that continuously recorded the specific conductivity of water at the bottom of the channel at the U.S. 17 bridge for a two-year period. In most cases there was less than 5 percent difference between the daily maximum recorded by the monitor and the conductivity of the daily sample. This indicates that once-daily sampling is sufficient to detect the presence of saltwater intrusion at this location.

A frequency analysis of the specific conductivity data from the 11 years of daily samples at New Bern (fig. 3.19) shows that at least some saltwater (as indicated by a specific conductance of 800 µmhos) was present along the channel bottom 60 percent of the time and along the surface, about 45 percent of the time.

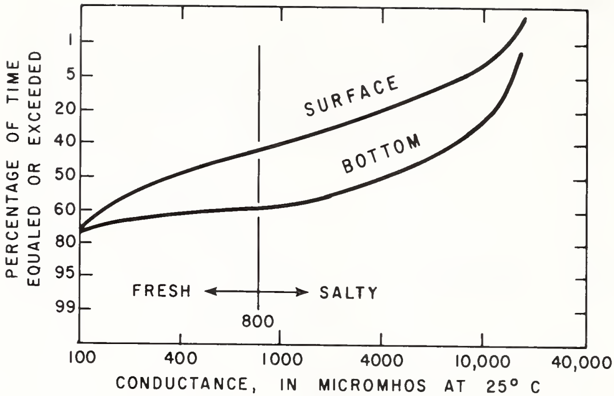


Figure 3.19.--Percentage of time specific conductances equaled or exceeded indicated values in the Neuse River estuary at New Bern, 1957-67.

The surface specific conductance-distance relation (fig. 3.18) and the surface specific-conductivity frequency curve (fig. 3.19) were used to estimate the frequency of occurrence of various specific conductivities at points in the estuary upstream from the U.S. Highway 17 bridge (fig. 3.20). These estimates are the dashed curves above the solid curve labeled "surface specific conductance at New Bern" on figure 3.20. It should be emphasized that these dashed curves are generated and only the solid curve is based on measured data.

As an example of the use of figure 3.20, suppose an industry desires process water which may have a conductance exceeding 800 μmhos not more than 5 percent of the time, with water during times of exceedance being provided by emergency storage. Where is the most downstream point along the Neuse River which could reasonably be expected to meet this criteria? From figure 3.20, the intersection of the 800-μmhos line and the 5 percent exceedance line falls between 6 and 8 miles upstream from the U. S. Highway 17 bridge at New Bern. The interpolated value would be about 7.5 miles. The industry in this example would probably not want to locate its water intakes any further downstream than this.

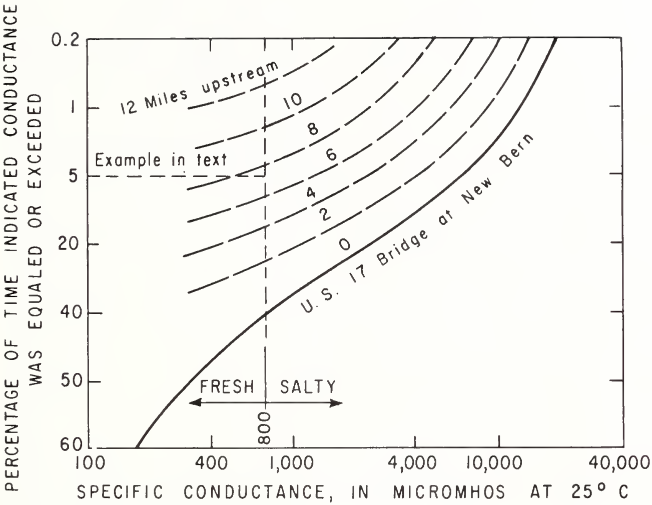


Figure 3.20.--Percentage of time surface specific conductances were equaled or exceeded for several locations in the Neuse River estuary, 1957-67.

In the Trent River estuary, daily samples were collected by the U.S. Geological Survey from 1959 through 1961 at a site 6.5 miles upstream from its confluence with the Neuse River at New Bern (station 02092558 on plate 1). The samples were integrated surface-to-bottom in a shallow part of the river where surface and bottom specific conductivities were nearly the same. A frequency analysis of the daily conductivities is shown in figure 3.21. The added dashed curves represent estimates of the frequency of occurrence of various specific conductivities at other points in the estuary. These dashed relations were generated by using the specific conductivity-distance relationship for the Trent River estuary (fig. 3.18).

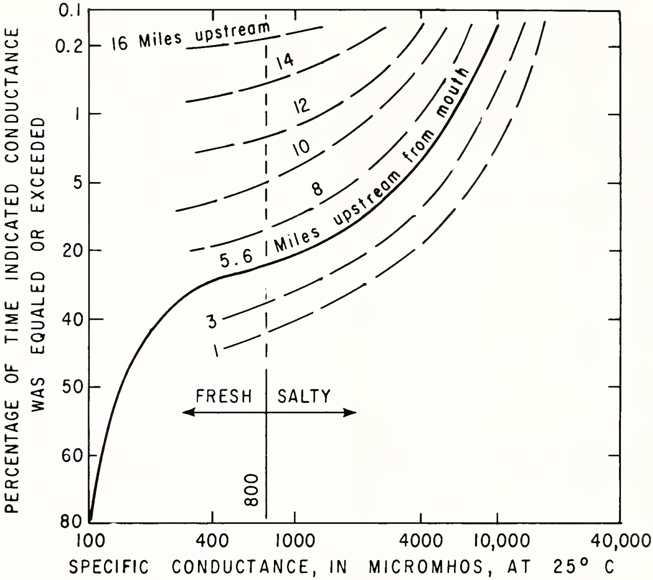


Figure 3.21.--Percentage of time integrated specific conductances were equaled or exceeded for several locations in the Trent River estuary, 1959-61.

Salinity data were collected at a number of other more downstream locations in the Neuse River estuary by the University of North Carolina Institute of Marine Sciences and the Carolina Power and Light Company. Data from four of the locations having the longest period of sampling have been analyzed to give some indication of the frequency of occurrence of various salinities. The data were collected at varying intervals, from days to months apart, but with good year-round coverage. Figures 3.22-3.25 present salinity frequency curves for these 4 locations, known as Garbacon Shoals Light, Wilkinson Point Light, Hampton Shoal Light, and Fort Point Light (plate 1).

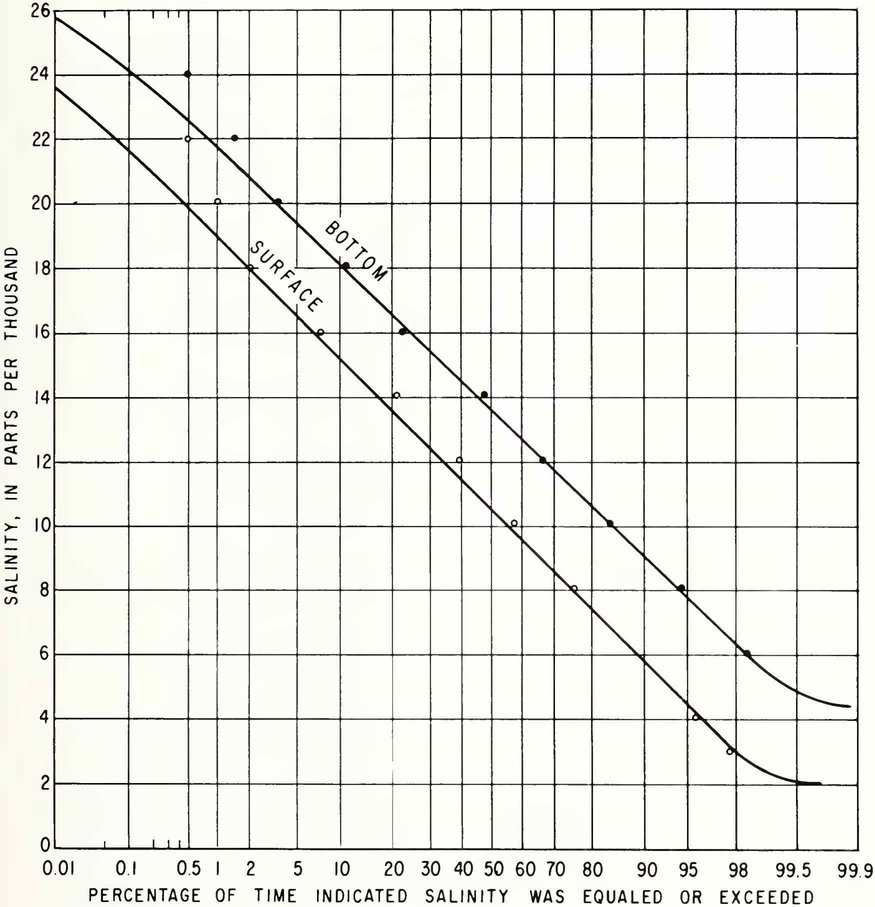


Figure 3.22.--Percentage of time surface and bottom salinities were equaled or exceeded in the Neuse River estuary at Garbacon Shoals Light, 1948-68. Data are from the University of North Carolina Institute of Marine Sciences, Morehead City, N.C., and Carolina Power and Light Company.

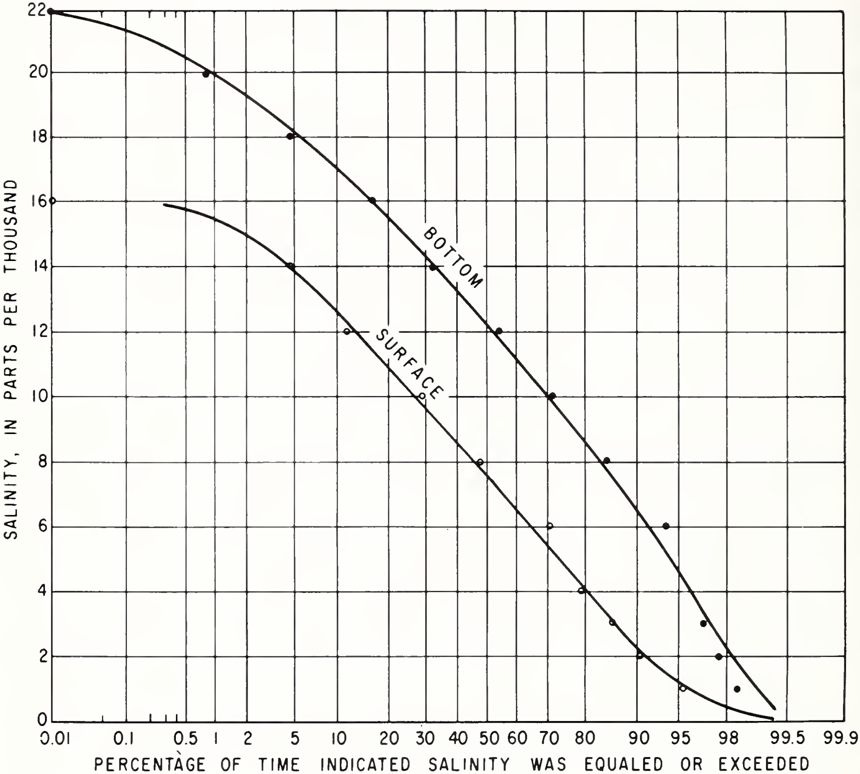


Figure 3.23.--Percentage of time surface and bottom salinities were equaled or exceeded in the Neuse River estuary at Wilkinson Point Light, 1958-67. Data are from the University of North Carolina Institute of Marine Sciences, Morehead City, N.C., and the Carolina Power and Light Company.

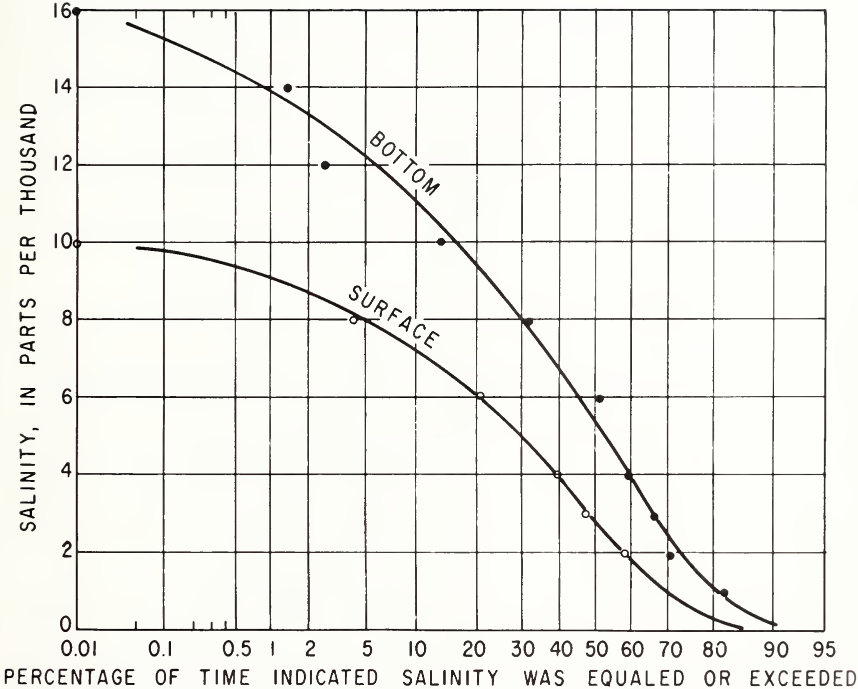


Figure 3.24.--Percentage of time surface and bottom salinities were equaled or exceeded in the Neuse River estuary at Hampton Shoals Light, 1958-60. Data are from the University of North Carolina Institute of Marine Sciences, Morehead City, N.C.

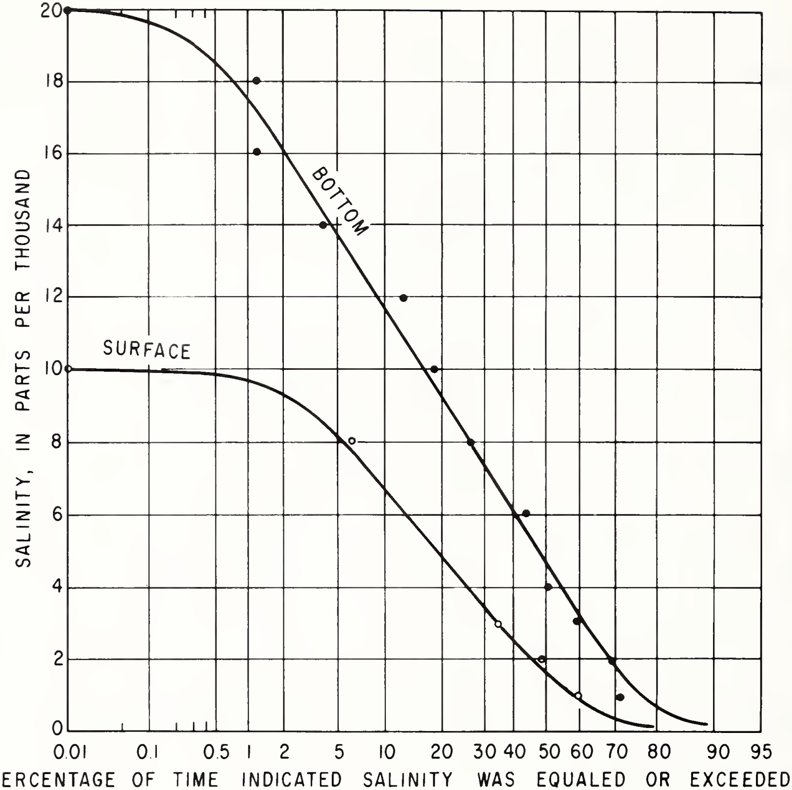


Figure 3.25.--Percentage of time surface and bottom salinities were equaled or exceeded in the Neuse River estuary at Fort Point Light, 1958-67. Data are from the University of North Carolina Institute of Marine Sciences, Morehead City, N.C.

The maximum known saltwater intrusion into the Neuse estuary occurred on Aug. 21, 1954, about 65 miles upstream from the mouth and 2.25 miles northeast of Fort Barnwell, when specific conductance averaged 673 μmhos (indicating about 160 mg/L of chloride). Saltwater has been detected upstream from Street's Ferry, 37 miles upstream from the mouth of the Neuse River (station 02091836 on plate 1) several times since 1955, but no intrusion to Fort Barnwell is known to have occurred since 1954. The point of maximum known intrusion in the Trent River estuary is about 4.5 miles upstream from Pollocksville, or about 28 miles upstream from the mouth of the Trent (60 miles upstream from the mouth of the Neuse). This extreme intrusion was caused by winds from Hurricane Hazel (October 15, 1954) which came during a severe drought when the rivers were experiencing very low flow.

Relation of Salinity to Freshwater Inflow

Although the relations in figures 3.19-3.25 give an overall indication of the frequency of saltwater intrusion at a number of locations in the Neuse-Trent river system, they do not separate the effects of variable freshwater inflows on the frequency of intrusion. During years of high freshwater inflow, when saltwater is displaced farther downstream than usual, the likelihood of high winds pushing saltwater upstream to, say, New Bern is less than during years of low freshwater inflow, when tides or wind-driven currents need not push the water as far upstream to reach New Bern.

To show these effects of freshwater inflow at key locations, specific conductance data for the Neuse River estuary at New Bern (sta. 02092162 on plate 1) were related to the annual freshwater discharge of the Neuse River at Kinston (fig. 3.26); and intrusion data for the Trent River estuary near New Bern (sta. 02092558 on plate 1) were related to annual freshwater discharge of the Trent River at Trenton (fig. 3.27). With these relations, it is possible to estimate the number of days when saltwater was present during a given year. For example, if the annual average discharge at Kinston was 1.08 $(ft^3/s)/mi^2$ for a given year, then water at the surface of the Neuse River estuary at New Bern would have been expected to have a specific conductance of 800 μmhos or greater 49 percent of the time (179 days) during that year, and the specific conductance of water at the channel bottom would be expected to exceed 800 μmhos 68 percent of the time (248 days for that year). Furthermore, such conditions have a 45 percent chance of occurrence for any year.

Management of the proposed Falls Lake project in the upper Neuse River basin, by augmenting low flows with reservoir storage, almost certainly would reduce the frequency of occurrence of the most extreme saltwater intrusion. By releasing flood storage at medium-high flow rates over a long period of time, the Falls Lake project may also reduce the number of days per year of occurrence of salty water at New Bern, but no rigorous analyses of this speculation has been made.

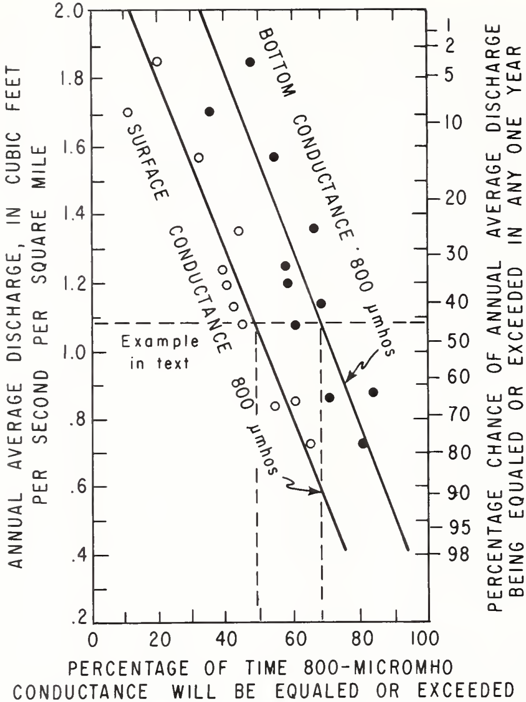


Figure 3.26.--Percentage of time a conductance of 800 µmhos will be equaled or exceeded in the Neuse River at New Bern for various annual average discharges at Kinston (drainage area - 2690 mi²).

Generally, conditions of minimum saltwater encroachment in the Neuse and Trent River estuaries occur during the month of April and maximum saltwater encroachment occur in December (figs. 3.11 and 3.12). This may seem surprising because maximum discharges of the Neuse River occur in February, on average, and minimums occur in June. However, changes in salinity due to changing freshwater discharge occur slowly in these estuaries because of the dampening effect of Pamlico Sound.

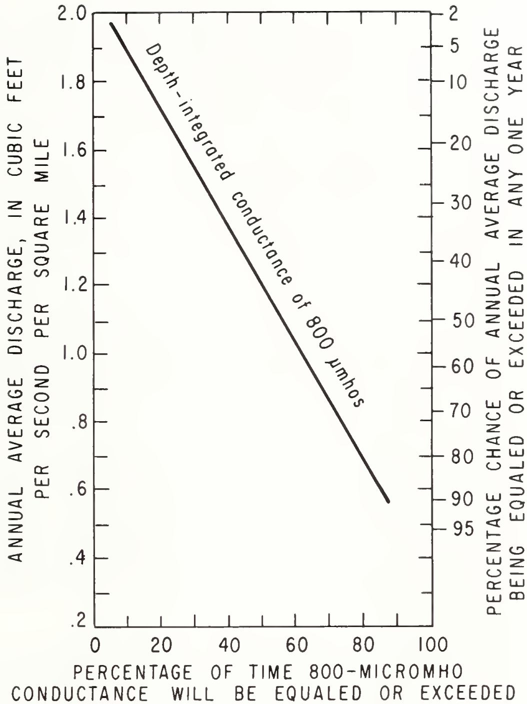


Figure 3.27.--Percentage of time a specific conductance of 800 μmhos will be equaled or exceeded in the Trent River near New Bern for various annual average discharges at Trenton (drainage area - 138 mi²).

The Tar-Pamlico River System

The Tar-Pamlico River system (plate 1) drains a total area of 4,300 mi^2, with an average annual outflow of about 5,400 ft^3/s. The upper part of the basin lies in the Piedmont Province and the lower part in the Coastal Plain. The largest tributary to the Tar-Pamlico River system is Fishing Creek (drainage area 860 mi^2). Other important tributaries include Cokey Swamp Creek, Conetoe Creek, Tranters Creek, and the Pungo River.

Actually, the Tar River and the Pamlico River are one and the same watercourse. Upstream from the mouth of Tranters Creek (plate 1), which is about 39 miles upstream from the mouth of the Pamlico River, it is known as the Tar River; downstream in the widening segment opening into Pamlico Sound, it is known as the Pamlico River.

A navigation channel is maintained in the Tar-Pamlico River by the U.S. Army Corps of Engineers to 200 feet wide and 12 feet deep from the mouth of the Pamlico River to Washington (about 38 miles upstream from the mouth of the Pamlico River); 100 feet wide and 12 feet deep from Washington to a turning basin at the mouth of Hardee Creek, a tributary to the Tar River; and 75 feet wide and 5 feet deep from Hardee Creek to Greenville.

The combined surface area of the Pamlico and Pungo Rivers is rather large, about 225 mi^2. However, depths are shallow, averaging only about 11 feet. The total volume of the Pamlico River estuary (including the open-water segment of the Pungo River) is about 69 billion ft^3.

The influence of ocean tides extends upstream to Greenville on the Tar River, about 59 miles upstream from the mouth of the Pamlico River estuary. Due to the dampening effect of Pamlico Sound, tide ranges near the mouth of the Pamlico River are less than 0.5 foot. However, due to the funnelling effect of decreasing channel dimensions in the upstream direction, tide ranges at Washington approach 1.0 foot. Tide ranges in the Tar River have not been studied, but decrease to nothing near Greenville.

As is the case in the Neuse-Trent system, winds play a far more important role than either lunar tides or freshwater inflow in generating currents and in changing water levels in the Pamlico River. For example, on Sept. 19, 1955, Hurricane Ione produced surges of about 7.0 feet above mean low water at Washington, as recorded on a U.S. Army Corps of Engineers recording tide gage.

Although saltwater intrusion in the Pamlico River occurs frequently, in the Tar River saltwater rarely penetrates more than a few miles upstream from the mouth. The greatest known penetration of saltwater into the Tar River occurred on Oct. 15, 1954 following an extreme drought period and during a large influx of saltwater due to Hurricane Hazel; on this day a specific conductance of 15,600 µmhos (5,800 mg/L chloride) was measured at Grimesland (sta. 02084171 on plate 1), which is about 4.7 miles upstream from the mouth of the Tar River. The likelihood of occurrence of an extreme drought followed immediately by a major hurricane is difficult to evaluate, but the recurrence interval of two such events occurring in succession is probably more than 100 years. If we assume that salinity gradients along the channel of the Tar are similar to observed gradients in the Pamlico, then the saltwater front (200 mg/L chloride) might have penetrated to about 16 miles upstream from the Grimesland station on that date.

Destructive algal blooms are a recurring problem in the Pamlico River estuary. Blooms of algae, predominantly dinoflagellates, occur each late winter or early spring and each summer (Hobbie, 1974). Hobbie attributes the winter blooms to high concentrations of nitrate in runoff from the Coastal Plain after crops are harvested and forest growth slows in the fall and winter. Summer blooms may be caused by a combination of moderately high concentrations of nutrients entering the estuary, utilization by algae of nutrients already present in the sediments in the estuary, and higher rates of biological productivity due to warmer temperatures.

Summer dieoffs of all or nearly all bottom-dwelling organisms in the Pamlico River are common when salinity stratification is present. At such times, the decomposition of dead organisms (including algae) on the river bottom may utilize all available oxygen, which is normally replenished by mixing with the more oxygen-rich water higher in the water column. However, stratification prevents or greatly inhibits this mixing, thus contributing to the death of fish as well as clams, other bivalves, snails, and marine worms.

Several investigators, including Hobbie (1974), have established that nitrogen rather than phosphorus is the limiting nutrient in producing algal blooms in the Pamlico River - phosphorus always being present in sufficient amounts to produce blooms. Carpenter (1971) showed that phosphate in the effluent discharged to the Pamlico River estuary from phosphate mining operations near Beaufort (plate 1) was superfluous to requirements for algae production in the estuary.

Davis and others (1978) found that substantial amounts of organic carbon and nutrients are trapped within the Pamlico River sediments and that these may be important contributors to algal blooms, particularly during the summer.

Water Levels

As previously mentioned, winds are the most important force affecting water levels in the Pamlico River. Winds from the east-southeast, blowing parallel to the channel axis, have the maximum effect in producing high water levels in the Pamlico River, while winds from the opposite direction, west-northwest, have the maximum effect in producing low water levels. The wind diagram (fig. 3.28) for resolving a given wind to the directional component effective in causing water level changes in the estuary is similar to the one prepared for the Neuse River estuary (fig. 3.13); values are based on the cosine of the angle between the actual direction of the wind and the direction causing the maximum effect. In the case of the Pamlico River, the axis of maximum effect forms an angle of about 110° from north.

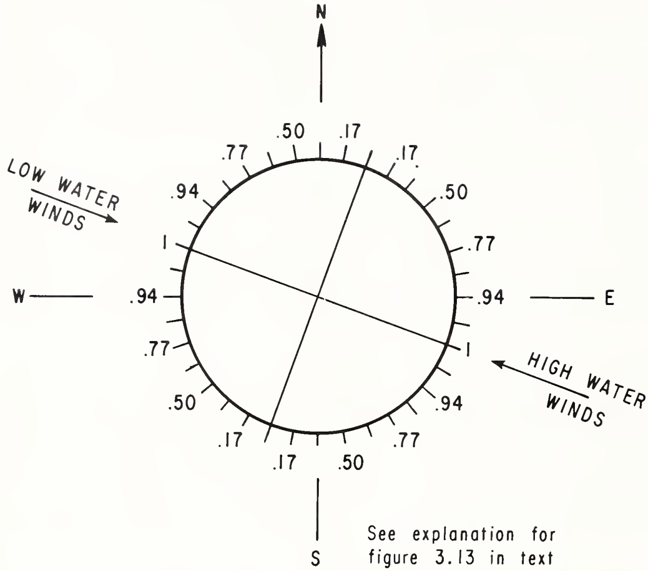


Figure 3.28.--Wind diagram for the Pamlico River estuary.

Figure 3.29 provides an example of the sensitivity of water levels in the Pamlico River to winds. Actual wind speeds for the period Feb. 22 - Mar. 2, 1966, as recorded at the National Weather Service station at Cape Hatteras, were resolved to their effective componenents along the channel axis of the Pamlico River and plotted below a hydrograph of water levels recorded by the Corps of Engineers for the same

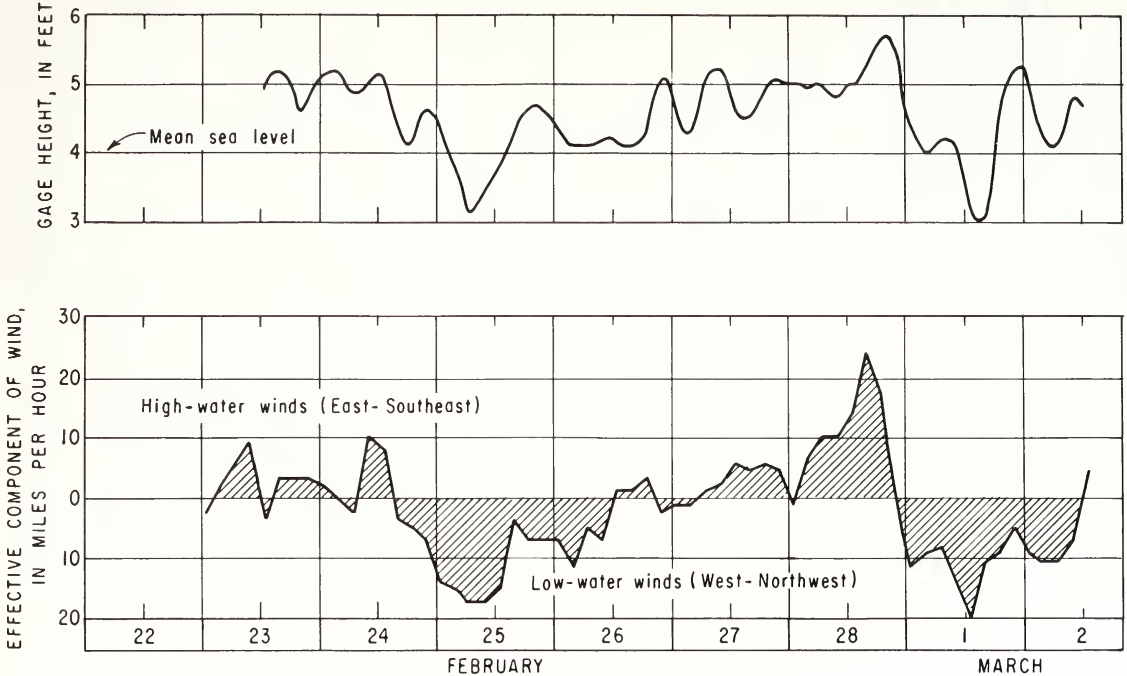


Figure 3.29.--Water levels in the Pamlico River at Washington and effective component of wind speed at Cape Hatteras, Feb. 22 - Mar. 2, 1966. Wind speeds are from National Weather Service records; water levels provided by the Corps of Engineers.

period for the Pamlico River at Washington. The close correlation is apparent. The response of water levels to wind is strong and immediate and, except for a lull in the winds on Feb. 26, the influence of lunar tides on water levels is completely overshadowed by wind effects.

Figure 3.30 relates the effective component of Cape Hatteras wind velocity to the change in water level of the Corps gage at Washington. The relation is of the same type presented earlier for the Neuse River at New Bern (fig. 3.14), for which an example of its use was given in the text. The relation may be used to predict the approximate rise in water level at Washington in response to east-southeast winds of various magnitudes. This information may prove of value in hurricane warnings and in assigning flood risks to streambank areas.

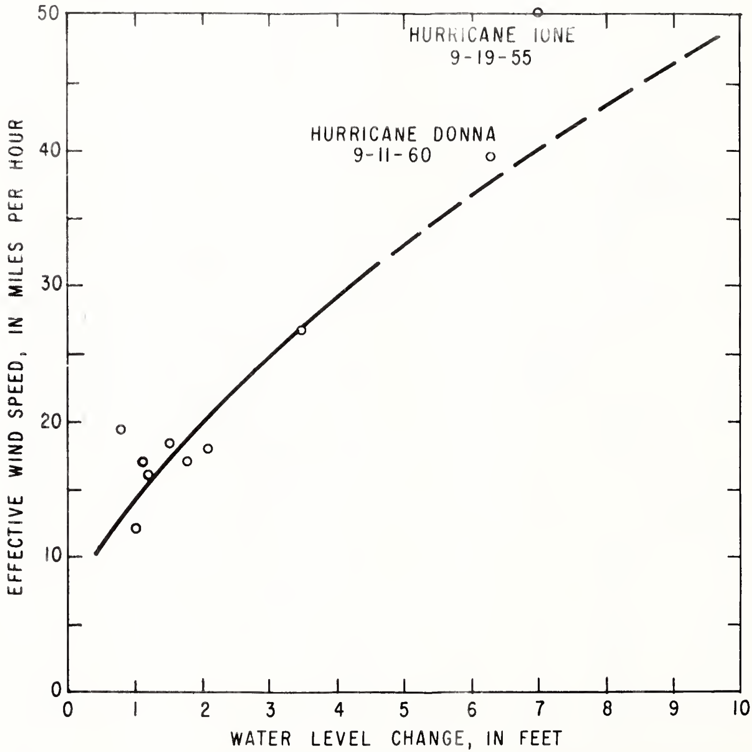


Figure 3.30.--Relation of rise in water level in the Pamlico River at Washington to effective wind velocity.

Flow

No flow measurements have been made either in the Pamlico River or in the tide-affected part of the Tar River. Therefore, some of what is said regarding flow in the Tar-Pamlico estuary is at least partly speculative. In the wide Pamlico River estuary, winds are undoubtedly the major short-term influence on flow, followed in importance by ocean tides and lastly, freshwater inflow. Freshwater inflow is probably more important in influencing short-term flows in the narrower Tar River than either winds or tides. However, freshwater inflow and the resulting net outflow are definitely the most important long-term influence on flow in both rivers.

The channel of the Pamlico River, unlike that of the lower Tar River, is vastly oversized for the amount of incoming freshwater it must carry. Therefore, velocities due to freshwater inflow are very low. For example, at the mouth of the Pamlico River, the average velocity due to the average annual freshwater outflow of 5,400 ft^3/s is less than 0.02 ft/s. On a monthly basis, estimated average freshwater outflows from the Pamlico River, in cubic feet per second, are as follows:

Jan. - 7,700	Apr. - 5,200	July - 3,500	Oct. - 3,700
Feb. - 10,000	May - 6,800	Aug. - 5,100	Nov. - 4,300
Mar. - 8,000	June - 2,400	Sept.- 3,200	Dec. - 4,900

Annual average flows vary considerably from year to year (fig. 3.31). For example, there is a 99 percent chance that the annual average flow at the Tar River at Tarboro (sta. 02083500 on plate 1) in any one year will be equal to or less than 1.8 $(ft^3/s)/mi^2$, but only a one percent chance that it will be equal to or less than 0.39 $(ft^3/s)/mi^2$.

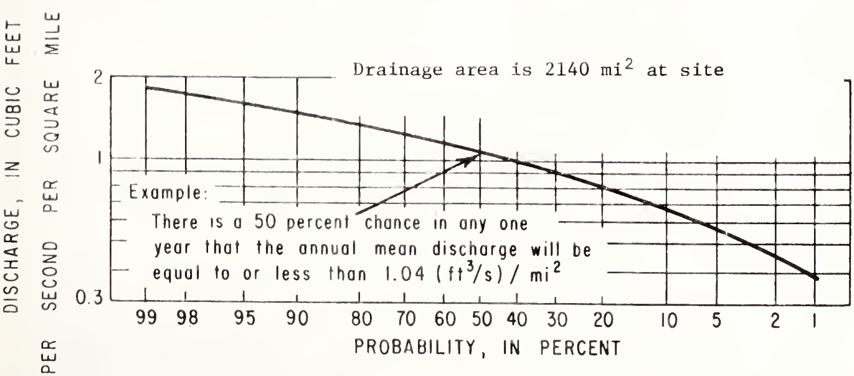


Figure 3.31.--Frequency curve of annual mean discharge of Tar River at Tarboro. After Wilder and others, 1978.

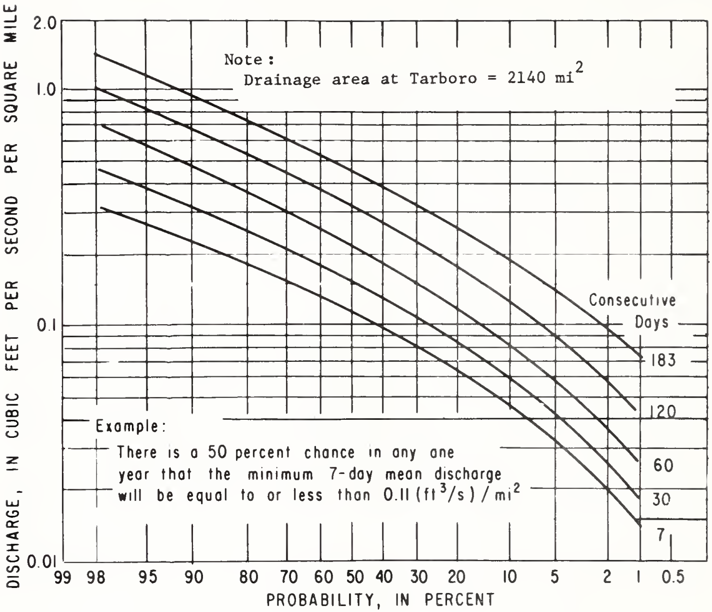


Figure 3.32.--Low-flow frequency curves of annual lowest mean discharge for indicated number of consecutive days for Tar River at Tarboro. After Wilder and others, 1978.

Likewise, within-year variations in low flows may be considerable (fig. 3.32). This type of low-flow information may be applied to studies of critical water supply, sewage dilution, and flow-related biological processes (including algal blooms).

High-flow frequency curves (fig. 3.33) give an indication of the amount of flushing that may take place in the spring months. Adequate flushing is a key factor in preventing destructive algal blooms, and high-flow frequency curves, used with historical data on algal blooms, may help to predict the frequency of occurrence of such blooms.

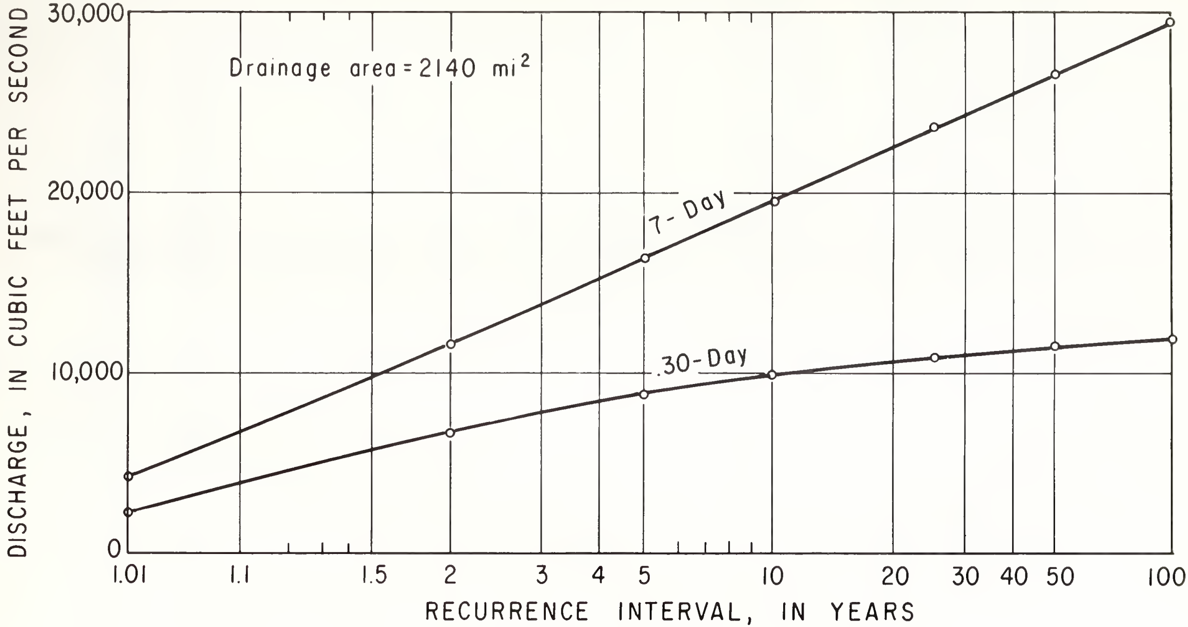


Figure 3.33.--Maximum 7 and 30 consecutive-day average discharges of the Tar River at Tarboro.

Water Quality

The chemical quality of the freshwater entering the Tar-Pamlico river system is usually, where not contaminated, of acceptable quality for public supplies and most industrial uses, with a minimum of treatment (table 3.5). Iron sometimes exceeds the 0.3 mg/L upper limit recommended by the Environmental Protection Agency (1976) [1978] for drinking water and color sometimes exceeds the recommended upper limit of 75 color units given in the same report, but these problems may be remedied with proper treatment. The cities of Tarboro and Greenville both withdraw water from the Tar River for municipal use, while the city of Washington utilizes water from Tranters Creek.

Figure 3.34 shows average monthly temperatures for the Pamlico River at Washington (sta. 02084472 on plate 1). The values are based on averages of daily surface and bottom temperature readings for the period October 1961 - September 1967. Typically, maximum temperatures occur in July or August and minimums in January or February.

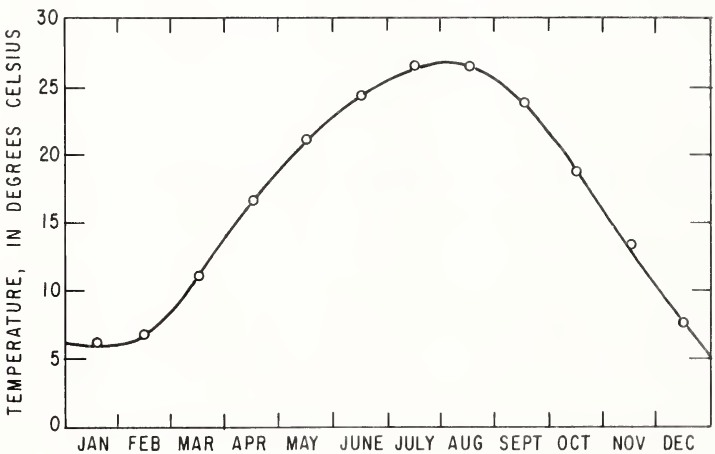


Figure 3.34.--Average monthly temperature of Pamlico River at Washington, October 1961 - September 1967.

Table 3.5.--Summary of chemical analyses of water samples collected at key stations in the Tar-Pamlico River basin. From Wilder and Slack, 1971a. Chemical concentrations shown are in milligrams per liter, except specific conductance, pH, and color.

Station number	Station oame	Drainage area in mi²	Period of sampling	Sampling frequency	Extreme and average	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids		Hardness as $CaCO_3$		Specific conductance (Micromhos at 25°C)	pH	Color
																		Residue at 180°C	Calculated	Calcium, magnesium	Non-carbonate			
02083500	Tar River at Tarboro, N.C.	about 2,140	Oct. 1944 to June 1968	daily	Max	19	.67	9.0	2.6	22	2.9	69	13	54	.3	6.8	1.0	111	102	33	14	270	7.7	140
					Min	6.2	.00	2.8	.5	3.0	.6	7	1.1	2.4	.0	.1	.00	45	33	9	0	47	5.6	3
					Avg	13	.16	5.4	1.6	7.6	1.8	24	5.9	7.6	.1	1.2	.31	64	50	20	2	83	....	35
02084000	Tar River at Greenville, N.C.	about 2,620	Oct. 1948 to Aug. 1967	monthly	Max	19	.72	9.2	2.6	12	2.6	32	15	15	.3	3.0	.30	79	79	32	11	121	7.4	120
					Min	3.7	.00	3.2	.8	2.9	.7	6	2.5	1.8	.0	.1	.00	44	30	13	0	39	5.4	7
					Avg	12	.22	5.2	1.6	6.2	1.8	21	6.7	6.6	.0	1.7	1.3	66	42	20	2	79	....	45
02084124	Tar River oear Pactolus, N.C.	about 2,680	Oct. 1956 to Sept. 1960	daily	Max	18	.56	9.0	3.2	12	2.8	76	19	20	.3	13	....	85	....	60	26	147	8.1	120
					Min	6.9	.00	3.4	.8	2.3	1.0	8	2.7	4.4	.0	.6	....	48	....	13	0	51	5.9	10
					Avg	12	.14	5.5	1.8	6.4	1.8	19	6.8	7.6	.1	2.3	....	65	....	21	5	81	....	45

Sediment

Little is known about the movement and deposition of sediment in the lower Tar River and Pamlico River, but the Geological Survey measures sediment discharge (excluding bed-load discharge) at the Tarboro station (mean daily sediment discharges are available from 1959-67; instantaneous discharges are available from 1974-present); a sediment-transport curve for this station is shown in figure 3.35. Sediment discharge there through 1976 averaged about 59 (tons/mi^2)/yr for the 2140 mi^2 drainage area. This value includes sediment contributions from about 500 mi^2 of the hilly Piedmont Province; thus, it is not typical of contributions from the lower 2,160 mi^2 of the basin which lies in the flat Coastal Plain Province. Data from Creeping Swamp and Palmetto Swamp watersheds (Winner and Simmons, 1977) indicates that sediment discharges from streams draining Coastal Plain areas of the lower Tar-Pamlico basin are significantly less than for streams draining the Piedmont Province. Values over the three-year period 1974-76 for 3 stations in the Creeping Swamp and Palmetto Swamp watersheds averaged about 38 (tons/mi^2)/yr and these values were considered high because of above average water discharge for those years. However, if we accept these values as typical of the 2,160 mi^2 area below the Tarboro station, then the average annual sediment yield of the entire Tar-Pamlico basin might be about 208,000 tons. The ultimate fate of all this sediment is uncertain, but at least some is deposited in the Tar and Pamlico River estuaries and some in Pamlico Sound. It is not known how much, if any, eventually reaches the Atlantic Ocean through the inlets to Pamlico Sound.

Salinity

Daily during the period Oct. 1961 - Sept. 1967, the U.S. Geological Survey determined surface and bottom salinity values in the Pamlico River at Washington (sta. 02084472 on plate 1) in terms of specific conductance and chloride concentrations. These point data were supplemented by 10 specific-conductance surveys made by boat during the period Sept. 14, 1954 - Sept. 27, 1968.

At low salinities, the Pamlico River water is usually well mixed vertically, but Geological Survey data suggests that stratification is common when specific conductance is greater than 800 μmhos (fig. 3.36) and bottom salinities may exceed surface salinities by 50 percent or more. Geological Survey data, as well as data compiled by Williams and others (1967), show that salinities are very often higher near the left bank (in the sense of facing downstream) than on the right. This phenomenon (due to the Coriolis component of acceleration of the earth's rotation), was discussed in the GENERAL HYDROLOGY section and appears more pronounced in the Pamlico River estuary than in any other North Carolina estuary.

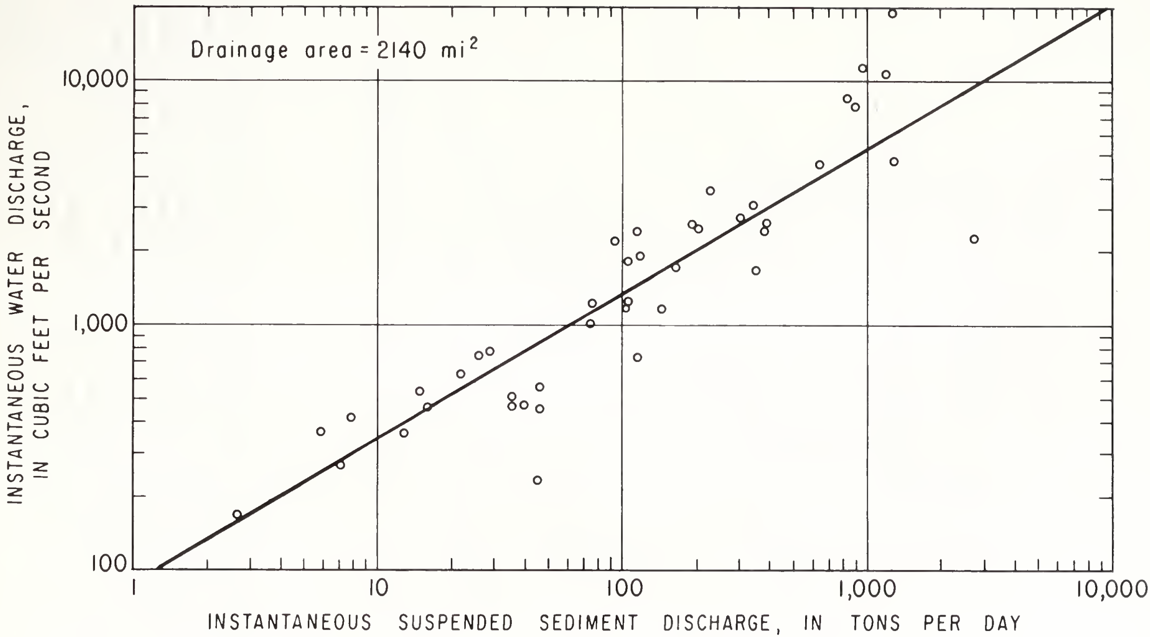


Figure 3.35.--Sediment-transport curve for the Tar River at Tarboro, based on measurements made during 1974-76.

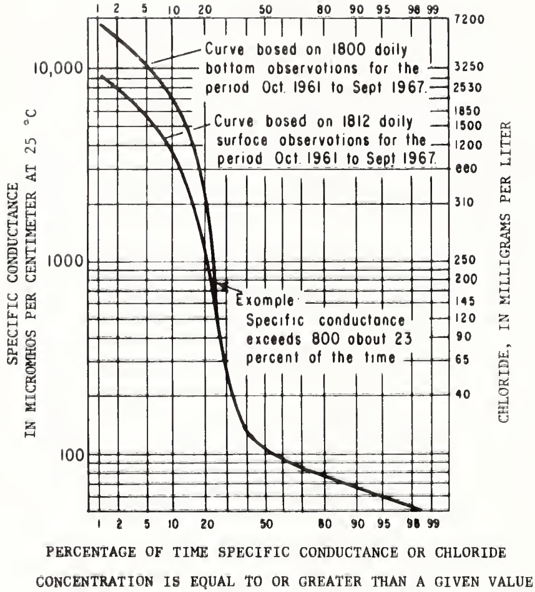


Figure 3.36.--Cumulative frequency curves of specific conductance and chloride, Pamlico River at Washington. After Wilder and others, 1978.

Conductivity surveys have shown that, wherever salty water is present within the Tar-Pamlico estuary, there is a relatively constant relation (fig. 3.37) between either surface or bottom specific conductance at one location and the corresponding surface or bottom specific conductance at other locations either upstream or downstream; this relation is applicable from the mouth of the Pamlico River upstream to a point in the Tar River about 6.5 miles upstream from its mouth at Tranters Creek - a total distance of 46.5 miles. In this reach, specific conductance gradients average about 610 μmhos/mi.

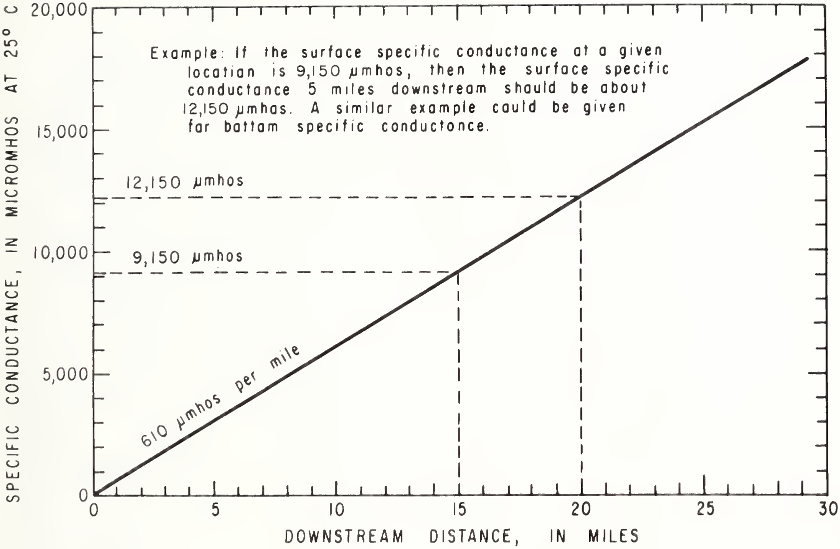


Figure 3.37.--Relation between surface specific conductance at one point in the Pamlico River estuary and surface specific conductance at other points either upstream or downstream.

Significant saltwater intrusion (200 mg/L chloride or more) is present at Washington only about 23 percent of the time (fig. 3.36), but the frequency of significant saltwater intrusion quickly increases in a downstream direction. At the mouth of the Pamlico River, chloride concentrations are seldom less than 2,000 mg/L, even during periods of high freshwater runoff.

The frequency of saltwater intrusion in the Pamlico River estuary is, of course, inversely related to freshwater inflow. Annual average discharges of the Tar River at Tarboro (sta. 02083500 on plate 1) were plotted against percent of time that a specific conductance of 800 μmhos or greater was recorded at Washington for each year during the period 1962-1967 (fig. 3.38). The interpretation of figure 3.38 is similar to that of figure 3.26 for the Neuse River estuary. The percent chance of occurrence (or recurrence interval) of a given annual average discharge and associated specific conductance conditions may be estimated from the right-hand ordinates.

Of greater interest, perhaps, is the movement of the saltwater front (200 mg/L chloride) in response to changing freshwater inflow from the Tar River (fig. 3.39). The shape of the curve indicates that when the saltwater front is at or downstream from Washington, a large change in freshwater inflow is required to produce significant movement of the

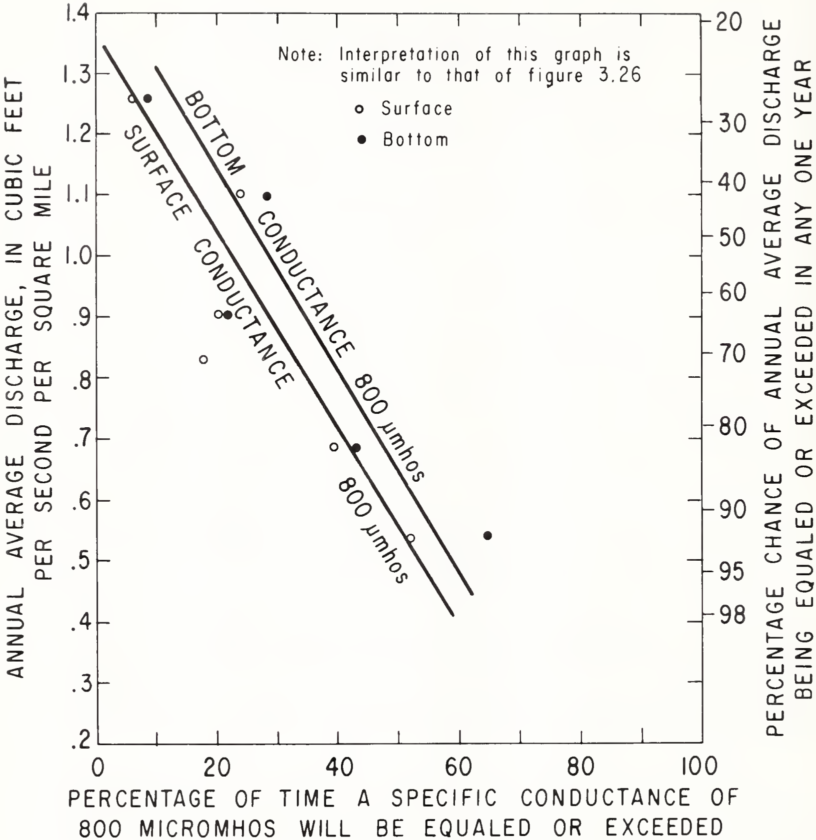


Figure 3.38.--Percentage of time a specific conductance of 800 µmhos will be equaled or exceeded in the Pamlico River at Washington for various annual average discharges at Tarboro (drainage area - 2,140 mi²).

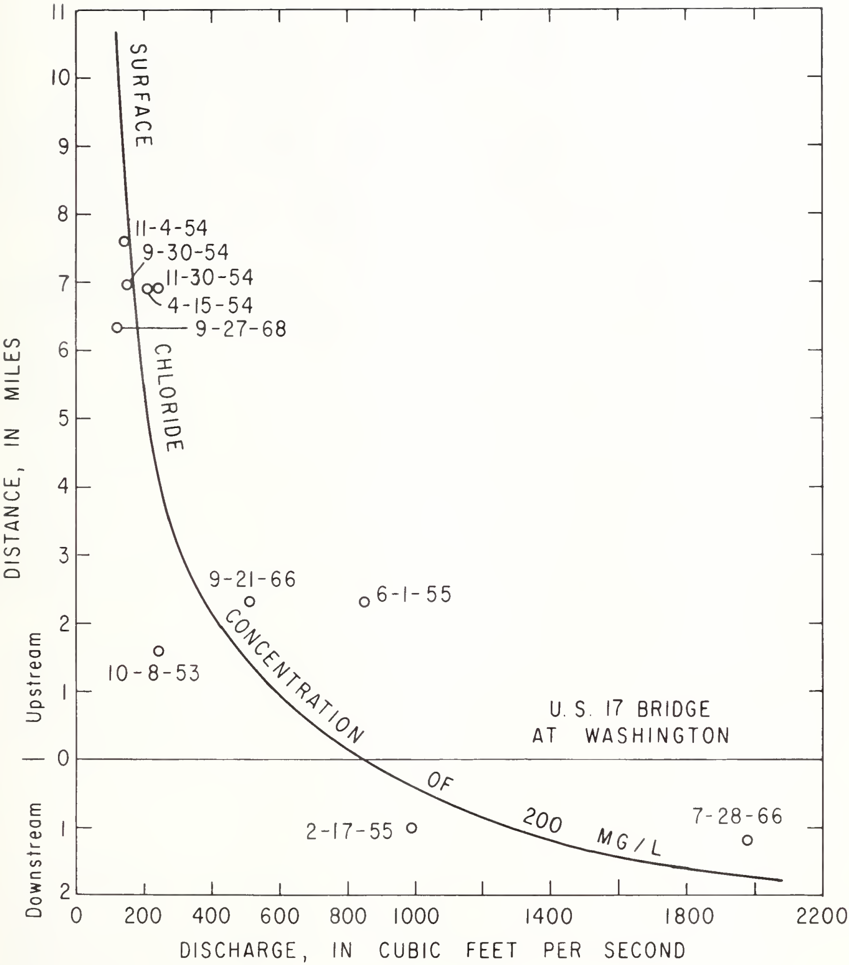


Figure 3.39.--Relation between the preceding 30-day average discharge of the Tar River at Tarboro and the location of the saltwater front. A 7-day lag time is applied to the 30-day flows.

front, whereas when the front is located 2 or more miles upstream from Washington, even a relatively small change in freshwater inflow may produce significant movement of the front. This general response pattern is typical of most estuaries. The relation of fig. 3.39, though not well defined for higher flow rates and fairly inaccurate at low flow rates, is useful in estimating the advance or retreat of the saltwater front under most flow conditions. The relation of fig. 3.39 may thus be useful in planning for withdrawals of freshwater for municipal or industrial supply and for evaluating the impact of induced salinity changes on estuarine organisms. Regarding the latter, the National Technical Advisory Committee to the Secretary of the Interior (1968) recommended that, based on studies of the effects of salinity changes on estuarine species, no changes in hydrography or stream flow should be allowed that would permanently change salinities in an estuary by more than 10 percent from natural variation.

CHAPTER 4

HYDROLOGY OF THE ALBEMARLE SOUND ESTUARINE SYSTEM

For purposes of this report, the Albemarle Sound system (plate 1) includes not only Albemarle, Currituck, Roanoke, and Croatan Sounds, but also the estuaries and associated drainage of the Roanoke, Chowan, Perquimans, Little, Pasquotank, North, Alligator, and Scuppernong Rivers and all other land areas tributary to Albemarle Sound. The system drains a total area of 18,359 mi^2.

Broadly speaking, the Albemarle Sound estuarine system has much in common with the Pamlico Sound estuarine system; that is, tide ranges are of small magnitude in most locations and winds play a major role in water circulation in the sounds and in the wide lower parts of the estuaries. The Albemarle Sound system has no direct outlet to the ocean, but connects to Pamlico Sound and Oregon Inlet through Croatan and Roanoke sounds. Hence, dampening of tides is greater in the Albemarle system than in the Pamlico system. Salinities are generally lower in the Albemarle system than in the Pamlico system for several reasons. First, the total average outflow from Albemarle Sound (17,300 ft^3/s) is larger relative to its volume (5,310,000 acre-ft) than Pamlico Sound (32,000 ft^3/s and 21,000,000 acre-ft). The higher current strength resulting from this is sufficient to more effectively block saline water from the system. Furthermore, seawater that does reach Albemarle Sound has already been diluted in Pamlico Sound.

The data on which the following discussions are based are from various sources. Plate 1 shows the location of key Geological Survey discharge and water-quality data-collection stations used to help define freshwater inflow, freshwater quality, and salinity characteristics within the Albemarle Sound system. Other data sources are acknowledged where appropriate.

Albemarle Sound and Vicinity

Albemarle Sound (plate 1) is a drowned river valley estuary which lies behind the North Carolina Outer Banks. The closest oceanic connection is to the south at Oregon Inlet. The sound covers an area of about 480 mi^2, has an east-west dimension of about 55 miles, and averages about 7 miles wide. Eight rivers, including the Roanoke and the Chowan, and Currituck Sound, drain into Albemarle Sound (total drainage area of 18,359 mi^2), which in turn drains through Croatan and Roanoke Sounds into the northern part of Pamlico Sound.

The maximum depth of the sound is almost 30 feet, but most of the central area of the bay is little more than 18 feet deep (fig. 4.1). The bottom sediments, which consist mainly of fine-to-medium sand around

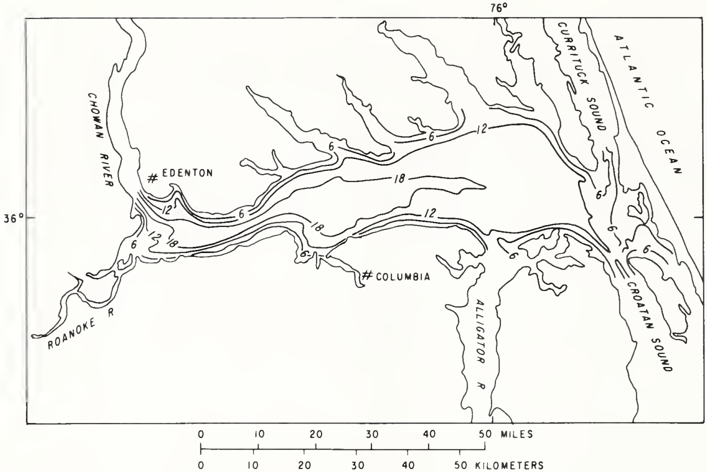


Figure 4.1.--Depth, in feet, of Albemarle Sound (from Pels, 1967).

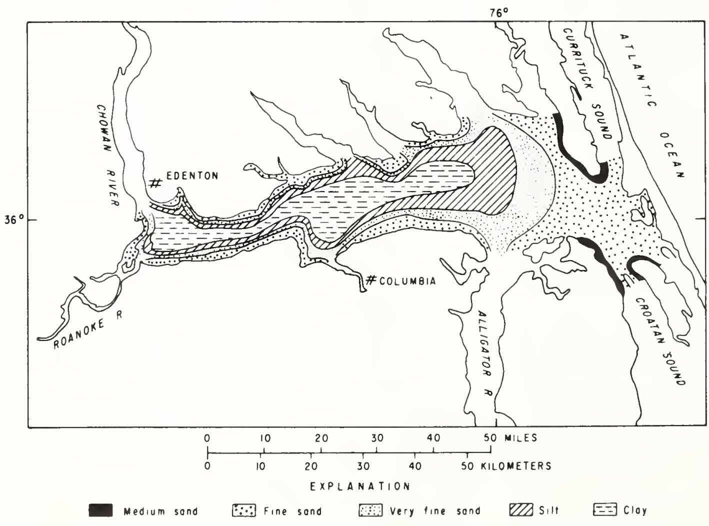


Figure 4.2.--Texture of bottom sediments in Albemarle Sound (modified from Pels, 1967, after Folger, 1972).

the margins of the sound (fig. 4.2), grade soundward to silt and clay in the deepest areas (Folger, 1972).

Albemarle Sound is an important link in the Atlantic Intracoastal Waterway. Albemarle Sound and its tributaries have proven to be exceptionally favorable habitats for anadromous fishes such as striped bass and herring and serve also as nurseries and commercial and sport fisheries for a variety of shellfish and finfish.

As a whole, Albemarle Sound is biologically healthy and shows few signs of cultural eutrophication (Bowden and Hobbie, 1977), although locally, some areas have been closed to shellfishing owing to high coliform bacteria counts and very destructuve algal blooms resulting in extensive fish kills have occasionally occurred in the Chowan River. Nutrients necessary for algal blooms (primarily compounds of nitrogen and phosphorous) are in relative abundance in Albemarle Sound. However, Bowden and Hobbie (1977) note that algae have so far never been very abundant in the open sound. They attribute the lack of algae growth in winter to a combination of low temperatures, insufficient light, and washout due to relatively high discharges. In summer, they credit high turbidity, which reduces the light supply, as the main factor preventing the algae from blooming.

Dissolved oxygen is abundant in Albemarle Sound year-round (Bowden and Hobbie, 1977). The percent oxygen saturation is almost always above 60 percent and is very often above 80 and 90 percent, with little difference between top and bottom concentrations at any location.

Water temperatures in Albemarle Sound closely follow air temperatures, as they do in Pamlico Sound. Minimum sound surface temperatures usually occur in January, averaging between 3 and 4°C for that month, and maximums usually occur in July, averaging 28°C (Williams and others, 1967). Variations across the open sound at any time are slight, seldom greater than 1 or 2°C, although tributary waters are almost always several degrees warmer. Vertical temperature variations are likewise small, or nonexistent, and surface-to-bottom decreases seldom exceed 2 to 3°C (Bowden and Hobbie, 1977).

Heath (1975) discussed potential water problems associated with recent large agricultural developments, including livestock operations, in the Albemarle-Pamlico peninsula. Artificial drainage canals designed to quickly remove runoff to the coast may lower salinities in coastal salt-marsh environments in southeastern Albemarle Sound to below levels necessary for developing shrimp, crabs, shellfish, and finfish. The runoff from these agricultural developments may also adversely affect the water quality of Albemarle Sound by contributing substantial amounts of bacteria, nutrients, pesticides, and sediment.

In Currituck Sound, extensive dense floating mats of Eurasian watermilfoil, an exotic species of freshwater aquatic plant, have hampered recreational use of large parts of the 153 mi^2 body of water. Among the possible solutions to this problem are application of herbicides, mechanical harvesting, and increasing the salinity of the sound to a level which would kill the watermilfoil. This last possible solution would require raising the salinity of the sound to about half sea-strength (Bailey and Haven, 1963), a measure that would not only destroy the watermilfoil, but also the existing freshwater ecological system, replacing it with a much more saline one.

Water Levels

Winds and tides are the most important short-term factors influencing circulation and water levels in Albemarle Sound, with freshwater inflow from tributaries playing a secondary role. The effect of winds from a given direction on water levels is difficult to analyze and varies with location in the sound and antecedent wind and water level conditions. In general, however, wind-driven currents from easterly winds will tend to produce lower water levels in the eastern end of the sound and higher water levels in the western end of the sound and in the Chowan and Roanoke estuaries. Wind-driven currents from westerly winds will usually have the opposite effect. Northerly winds tend to cause lower water levels along the northern shores of the sound and in the estuaries there and higher water levels along the southern shore of the sound and in the estuaries there. Southerly winds tend, of course, to have the opposite effect. Table 4.1, developed from water-level records of the U.S. Army Corps of Engineers and wind data from a National Weather Service station at Elizabeth City, shows the general effects of winds on water levels at 11 locations in Albemarle Sound and vicinity.

Concurrent records of wind and water levels at several locations in Albemarle Sound (fig. 4.3) tend to confirm the validity of table 4.1, but they also show the role of antecedent conditions in determining water level response to winds. For example, southeast winds on July 29, 1960, caused rising water levels near Edenhouse and Elizabeth City; this is in agreement with general effects predicted from table 4.1. Likewise, falling water levels on November 30, 1960, due to north-northwest winds agree in general with table 4.1. On the other hand, falling water levels at Elizabeth City during July 30, 1960 are counter to the general effects given in table 4.1. Water levels, high on July 29 because of easterly winds, began falling even with the change to westerly winds early on July 30. Apparently, the return flow from the water pileup on July 29 overwhelmed the expected tendency towards rising water levels at Elizabeth City due to westerly winds early on July 30.

Hurricane-force winds may cause much greater changes in water levels than the 1 to 2 foot changes seen in figure 4.3. Hurricane Donna caused rises of more than 4 feet above mean sea level at Edenton and

Table 4.1.--Relative effects of wind on vertical movement of water levels at selected locations in and near Albemarle Sound

Location	Wind direction															
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Chowan River near Edenhouse	1/ F	2/ V	3/ R	R	R	R	R	V	V	V	V	F	F	F	F	F
Perquimans River at Hertford	F	V	R	R	R	R	R	R	R	V	V	V	F	F	F	F
Little River near Nixonton	F	V	V	R	R	R	R	R	R	R	R	R	V	V	F	F
Pasquotank River at Elizabeth City	F	F	F	V	V	R	R	R	R	R	R	R	R	V	F	F
North River near Coinjock	F	F	F	F	F	V	R	R	R	R	R	R	R	R	V	F
Currituck Sound at Point Harbor	R	V	F	F	F	F	F	F	V	V	R	R	R	R	R	R
Albemarle Sound near Kill Devil Hills	R	V	F	F	F	F	F	F	V	V	R	R	R	R	R	R
Roanoke Sound near Manteo	R	R	V	F	F	F	F	F	V	V	V	R	R	R	R	R
Croatan Sound near Manns Harbor	R	R	V	F	F	F	F	F	V	V	V	R	R	R	R	R
Alligator River near Fort Landing	R	R	R	V	V	V	V	F	F	F	V	R	R	R	R	R
Scuppernong River at Columbia	R	R	R	R	R	R	V	V	V	V	F	F	V	R	R	R

1/ F = Falling water levels

2/ V = Variable effect

3/ R = Rising water levels

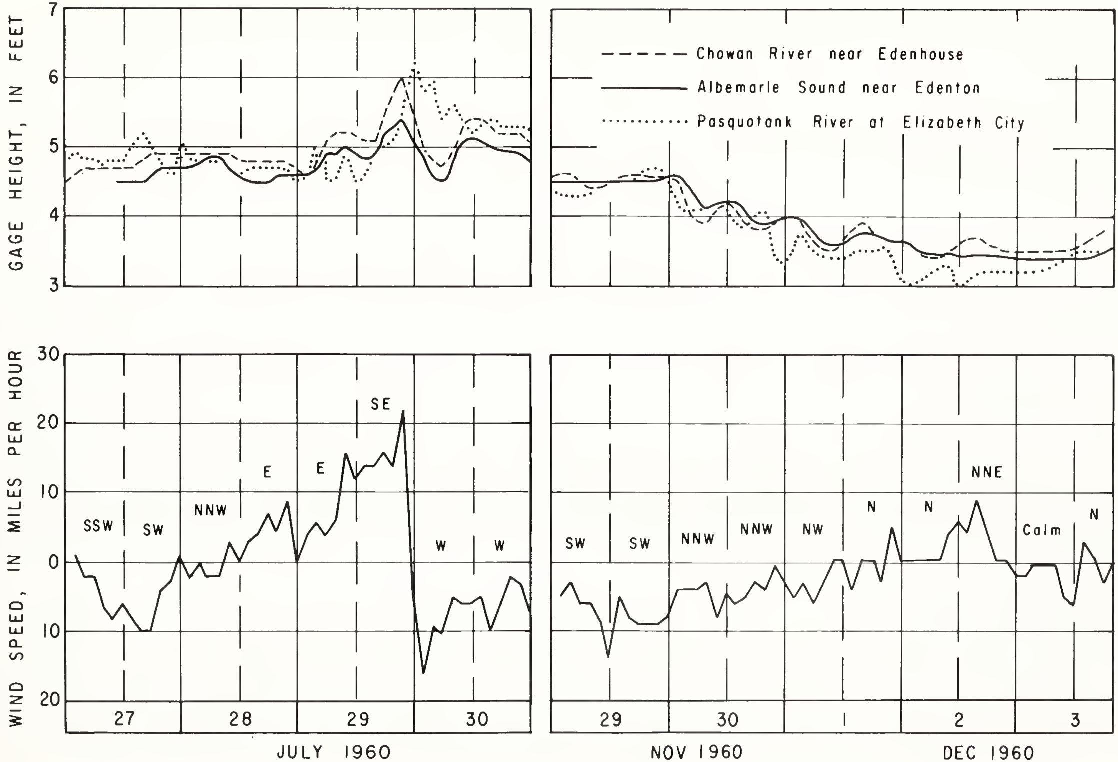


Figure 4.3.--Wind speed at Elizabeth City and water levels at Chowan River near Edenhouse, Albemarle Sound near Edenton, and Pasquotank River at Elizabeth City, July 27-30 and Nov. 29 - Dec. 3, 1960. Water level records are from tide gages operated by U.S. Army Corps of Engineers.

Elizabeth City during Sept. 11, 1960, and even greater rises, causing extensive flooding, occurred during Hurricane Ione on Sept. 19, 1955. Superimposed on the 1 to 2 foot water-level fluctuations attributable to winds are semidiurnal fluctuations in the range of about 0.5 foot. These are attributable to ocean tides. Although no measurements of tidal exchange for Albemarle Sound were made during this study, it is apparent from figure 4.3 that they are much less important than winds in determining water levels at the locations indicated and, by inference, elsewhere in the sound.

The relative unimportance of freshwater inflow compared to tidal exchange in determining water levels in Albemarle Sound and vicinity may be judged by a statement by Bowden and Hobbie (1977) to the effect that the input of water to the sound from a flood tide ranges from 11 to 18 times as much as the input from freshwater inflow. However, when considering net movement of water into and out of the sound over long periods of time, the effects of winds and tides tend to cancel, leaving freshwater inflow the most important factor in long-term net flow.

Freshwater Inflow

Table 4.2 is a gross water budget for Albemarle Sound, showing average monthly and annual values for <u>precipitation</u> on and <u>evaporation</u> from Albemarle Sound and its associated open-water areas, <u>inflow</u> from the Chowan River and Neuse River estuaries and from other land areas tributary to Albemarle Sound, and <u>outflow</u> to Pamlico Sound through Croatan and Roanoke Sounds.

Precipitation values for these areas are based on long-term averages from National Weather Service stations at Elizabeth City, Manteo, and Plymouth. Evaporation values are based on long-term averages of Maysville pan evaporation data (after applying a 0.7 pan coefficient). The area considered for direct precipitation and evaporation includes not only the 480 mi^2 of Albemarle Sound proper, but also 453 mi^2 of open-water area including Currituck Sound and the lower parts of the North, Pasquotank, Little, Perquimans, and Alligator Rivers (the open-water area of the Chowan River is not included in the total). Inflow from land areas other than the Chowan and Roanoke river basins (item E in table 4.2) includes drainage from the Albemarle-Pamlico peninsula to the south, the land area to the north of the sound extending into Virginia, and a small part of the Outer Banks to the east (total of 2,817 mi^2). The inflows from the Roanoke River basin were based on extensions to the mouth of long-term Geological Survey streamflow records of the Roanoke River at Roanoke Rapids (sta. 02080500 on plate 1). It is important to note here that the Roanoke River is regulated by a number of reservoirs in the basin, notably Kerr Lake and Roanoke Rapids Lake (plate 1). These may be controlled to mitigate flooding and ensure adequate flow during drought. Inflows from the Chowan River basin were

Table 4.2.--Monthly and annual gross water budget for Albemarle Sound

Element of Gross water budget	Drainage area in square miles	Average monthly and annual values, in cubic feet per second												
		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average annual
A. Precipitation on Albemarle Sound and associated open-water areas	933	2,800	3,400	2,900	2,500	2,800	3,600	5,400	5,000	4,300	2,500	3,000	2,600	3,400
B. Evaporation from Albemarle Sound and associated open water areas	933	1,000	1,700	2,200	3,400	3,900	4,200	4,100	3,500	2,800	1,800	1,400	900	2,600
C. Inflow from Chowan River Estuary at mouth near Edenton	4,943	6,500	9,100	8,600	6,600	3,700	2,600	3,000	3,500	3,000	2,200	2,500	4,400	4,600
D. Inflow from Roanoke River Estuary at mouth near Plymouth	9,666	10,000	12,000	10,000	11,000	10,000	8,500	8,000	7,500	6,500	6,500	7,500	8,300	8,900
E. Inflow from land areas not included in above elements	2,817	4,200	5,900	5,600	4,300	2,400	1,700	1,900	2,200	2,000	1,400	1,600	1,300	2,900
F. Total outflow of Albemarle sound into Pamlico Sound F = A - B + C + D + E	18,359	23,000	28,000	25,000	21,000	16,000	12,000	14,000	15,000	13,000	11,000	13,000	16,000	17,000

generated by extending to the mouth Geological Survey records from the Blackwater River near Franklin, Virginia and Potecasi Creek near Union, North Carolina (stas. 02049500 and 02053200 on plate 1).

As presented in table 4.2, February is the month of maximum outflow from the sound and October is the month of minimum outflow. The latter observation is in some contrast to the situation in Pamlico Sound, where minimum outflows occur in June, the month when evaporation rates are greatest. Because of the smaller size of Albemarle Sound and its relatively greater inflow, compared to Pamlico Sound, evaporation does not play as large a role in its water budget. However, during times of minimum precipitation and very low freshwater inflow, evaporation can be the largest item in the water budget of the sound. Figure 4.4 shows estimated low-flow frequency relations for 7 and 30 day periods for all inflow from the 17,426 mi^2 area tributary to Albemarle Sound. These relations are similar to those developed earlier for Pamlico Sound and do not account for inflow due to direct precipitation on Albemarle Sound and its associated open-water areas. If the minimum 30-consecutive-day 50-year inflow of about 1,500 ft^3/s were to occur in June of a given year, and if we further assume that precipitation is negligible for the month, while evaporation is average (4,200 ft^3/s from table 4.2), then the net outflow to Pamlico Sound for that month would be negative, that is (0 + 1,500 - 4,200) ft^3/s, or -2,700 ft^3/s. A negative value such as this indicates that there is a net inflow at this rate from Pamlico Sound to Albemarle Sound through Croatan and Roanoke Sounds.

High flow frequency curves are also of interest because they give an indication of the amount of flushing that may take place in Albemarle Sound during the late winter and early spring (fig. 4.5), and this is an important factor in limiting algal blooms. For example, the maximum 30-consecutive-day 10-year average inflow from areas tributary to Albemarle Sound is about 64,000 ft^3/s. At this rate, the volume of inflow would be equal to the volume of Albemarle Sound (5,310,00 acre-ft) in just 6 weeks, compared to the 14 weeks required for inflow to Pamlico Sound to equal the volume of the sound at the 30-day 10-year flow level.

Extent and Duration of Saltwater Intrusion

The salinity of Albemarle Sound is usually at a minimum in March as a result of heavy spring runoff displacing saline water seaward, and is at a maximum in December, after relatively low freshwater inflows during the summer and fall have allowed saline water to again advance landward (figs. 4.6 and 4.7). Although values given are for the water surface, the mixing effects of tides and winds are usually sufficient to prevent any significant salinity stratification in the open sound and surface-to-bottom increases seldom exceed 2 or 3 percent. Not only is Albemarle Sound generally less saline than Pamlico Sound, but the seasonal variations in its salinity are less than in Pamlico Sound. The seasonal

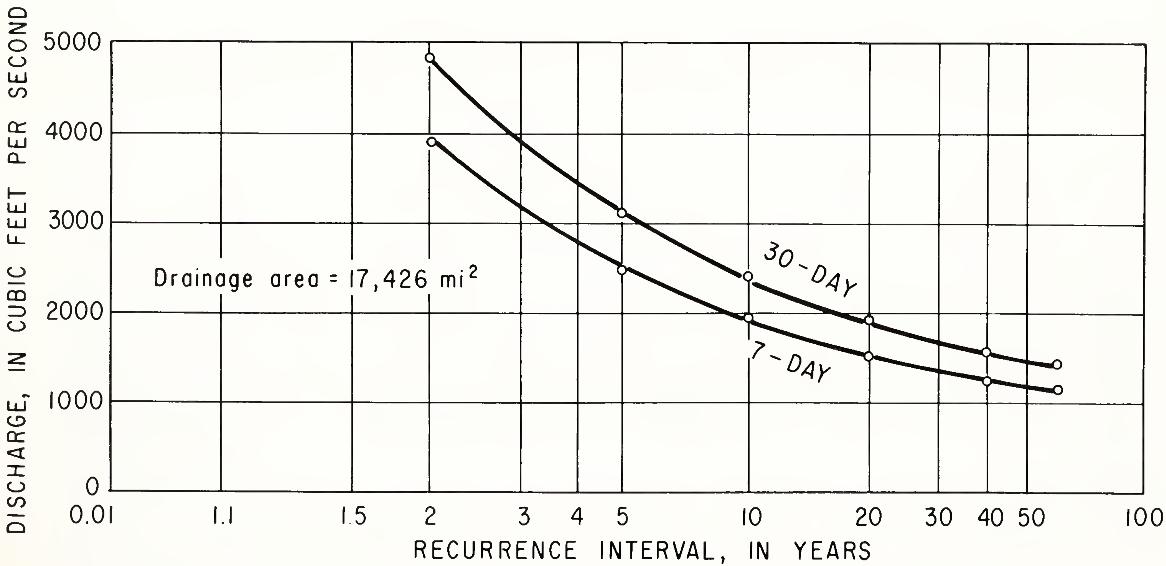


Figure 4.4.--Minimum 7 and 30 consecutive-day average inflow to Albemarle Sound from land drainage (not adjusted for precipitation on and evaporation from open-water areas).

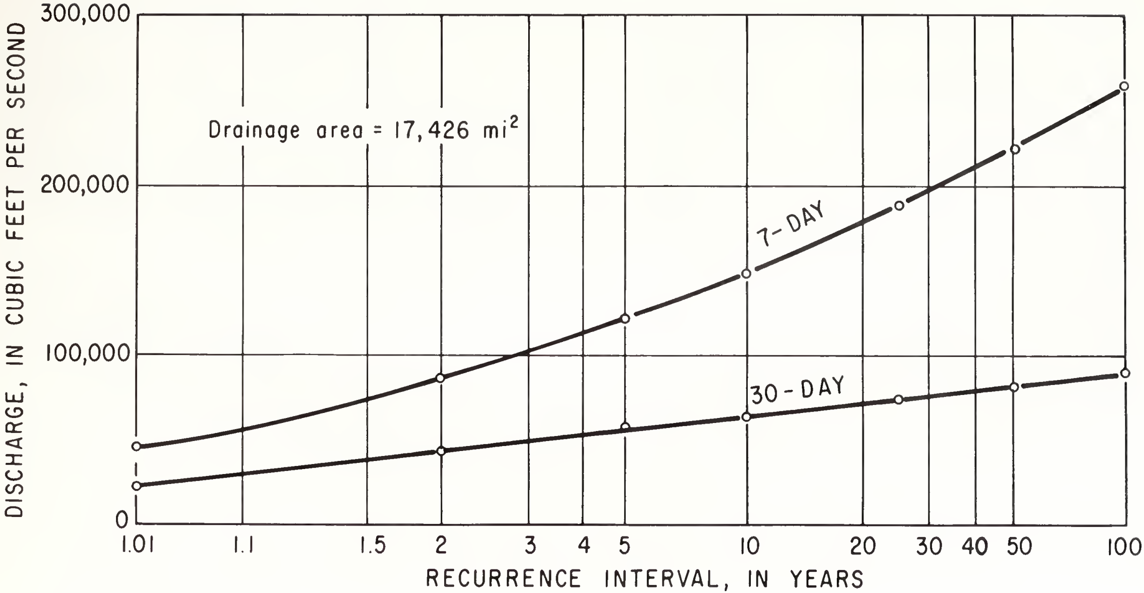
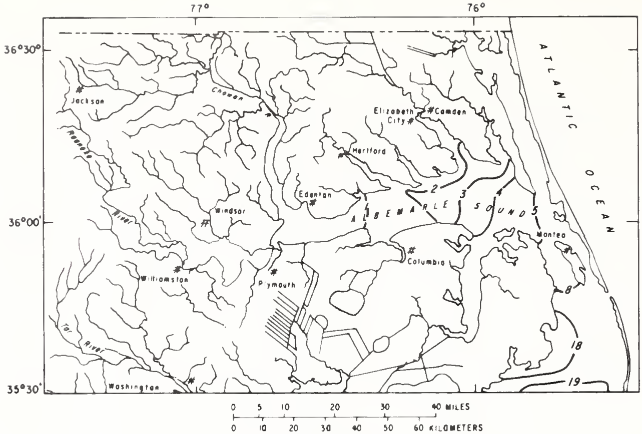


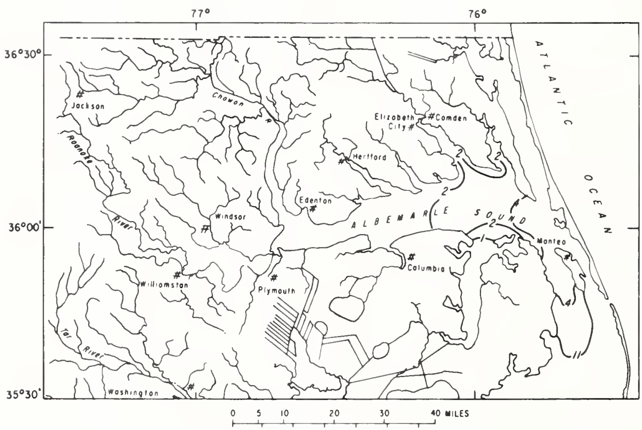
Figure 4.5.--Maximum 7 and 30 consecutive-day average inflow to Albemarle Sound from land drainage (not adjusted for precipitation on and evaporation from open-water areas).



EXPLANATION

—8— Salinity, in grams per kilogram. (Sea water contains about 34.5 grams of dissolved solids per kilogram of sea water.) Salinity interval variable

Figure 4.6.--Average surface salinity of water in Albemarle Sound and vicinity during the month of March (modified from Williams and others, 1967).



EXPLANATION

—4— Salinity, in grams per kilogram. (Sea water contains about 34.5 grams of dissolved solids per kilogram of sea water.) Salinity interval variable

Figure 4.7.--Average surface salinity of water in Albemarle Sound and vicinity during the month of December (modified from Williams and others, 1967).

pattern of saltwater intrusion in the Albemarle Sound near Edenton (station 02081155 on plate 1) is also evident from the specific conductance data in figure 4.8.

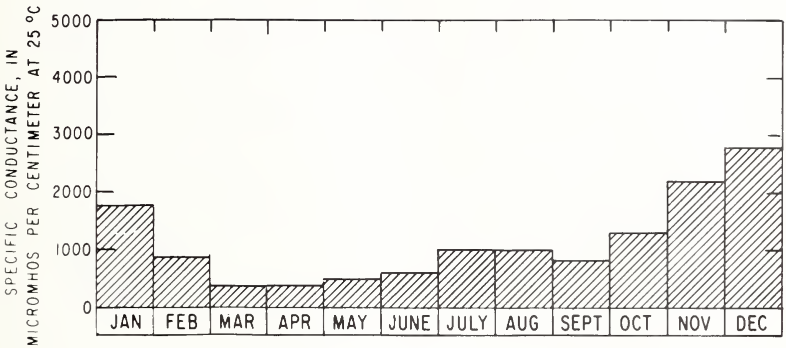


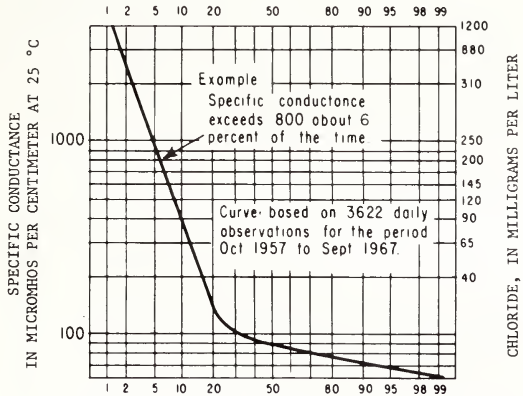
Figure 4.8.--Average monthly specific conductance of Albemarle Sound near Edenton, 1957-67.

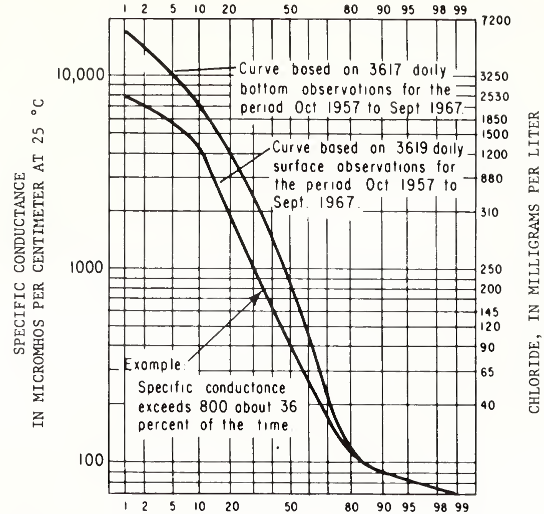
The extent and duration of saltwater intrusion into the estuaries of Albemarle Sound is a subject of importance because many of these estuaries represent potential sources of water for industrial and agricultural uses and are (or in some cases may be) suitable nursery areas for a variety of commercially valuable shellfish and finfish. The U.S. Geological Survey determined daily specific conductance of water at 9 stations in the Albemarle Sound estuarine system (plate 1) for various time periods between October 1954 and December 1968 (table 4.3) in order to determine the extent and frequency of saltwater intrusion in the Sound and its tributaries. These station data were supplemented by numerous specific conductance and chloride determinations made of water samples from a large number of other locations; these were used to help define the 2-year maximum upstream extent of saltwater intrusion (water containing 200 mg/L chloride) under non-hurricane conditions, as shown on plate 1.

Figures 4.9-4.15 from Wilder and others (1978) show the duration of intrusion of saline water at seven of the nine stations on plate 1. In many cases, separate duration curves are shown for the entire period of record and for the years of maximum and minimum saltwater intrusion.

Table 4.3.--Maximum chloride concentrations and specific conductance of water at daily sampling stations in the Albemarle Sound estuarine system. (B) indicates bottom sample. See plate 1 for locations.

Station No.	Name	Period of record	Maximum chloride concentration in milligrams per liter	Maximum conductance in micromhos 25°C
02043852	Pasquotank River near Elizabeth City, N. C.	Oct. 57-Sept. 67	1,940 Oct. 15, 1961	6,380 Oct. 15, 1961
02043862	Pasquotank River at Elizabeth City, N.C.	Oct. 57-Sept. 67	8,020 (B) Oct. 30, 1958	20,800 (B) Oct. 29, 1958
02043892	Perquimans River at Hertford, N.C.	Oct. 57-Sept. 60	1,290 Dec. 25, 1958	4,290 Dec. 25, 1968
02050160	Chowan River near Eure, N.C.	Oct. 67-Dec. 68	–	880 μmhos Dec. 19, 1967
02053244	Chowan River at Winton, N.C.	Oct. 54-Sept. 67	398 Dec. 15, 1958	1,400 Dec. 13 and 15, 1958
02053652	Chowan River near Edenhouse, N.C.	Oct. 57 Sept. 67	9,140 (B) Nov. 11, 1958	23,500 (B) Nov. 11, 1958
02081155	Albemarle Sound near Edenton, N.C.	Oct. 57-Sept. 67	12,100 (B) Nov. 3-6, 1958	30,600 (B)
02081166	Scuppernong River near Creswell, N.C.	Oct. 59-Sept. 67	2,270 June 18, 1967	7,260 June 18, 1967
02081172	Scuppernong River at Columbia, N. C.	Oct. 63-Sept. 67	2,980 June 5, 1967	9,300 June 5, 1967

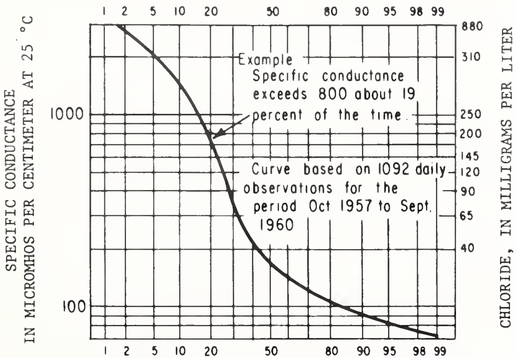


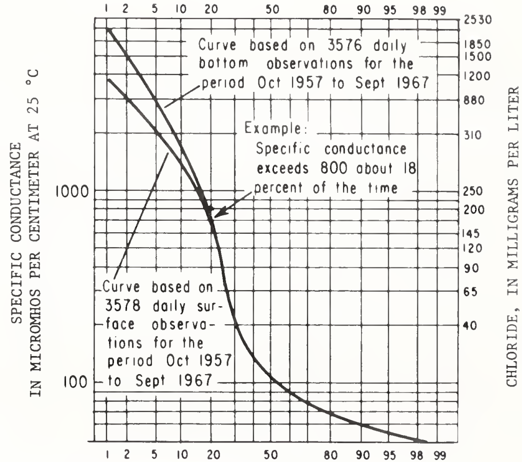


PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL TO OR GREATER THAN A GIVEN VALUE

Figure 4.9.--Cumulative frequency curve of specific conductance and chloride, Pasquotank River near Elizabeth City (Sta. 02043852 on plate 1). From Wilder and others, 1978.

Figure 4.10.--Cumulative frequency curves of specific conductance and chloride, Pasquotank River at Elizabeth City, (sta. 02043862 on plate 1). From Wilder and others, 1978.

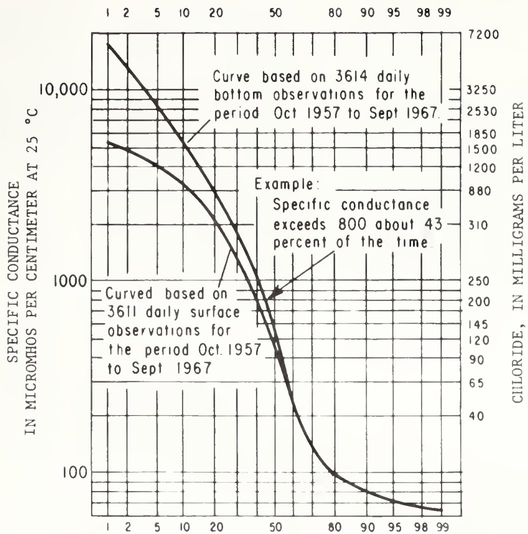


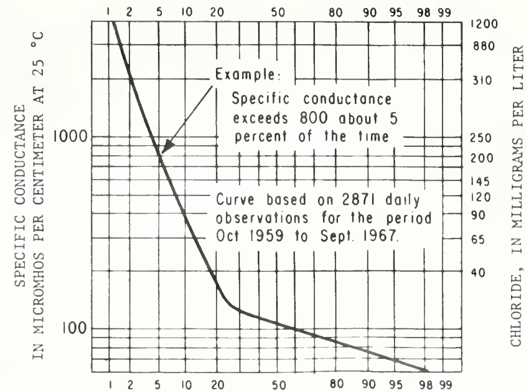


PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL TO OR GREATER THAN A GIVEN VALUE

Figure 4.11.--Cumulative frequency curve of specific conductance and chloride, Perquimans River at Hertford (sta. 02043892 on plate 1). From Wilder and others, 1978.

Figure 4.12.--Cumulative frequency curves of specific conductance and chloride, Chowan River near Edenhouse (sta. 02053652 on plate 1). From Wilder and others, 1978.





PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL TO OR GREATER THAN A GIVEN VALUE

Figure 4.13.--Cumulative frequency curves of specific conductance and chloride, Albemarle Sound near Edenton (sta. 02081155 on plate 1). From Wilder and others, 1978.

Figure 4.14.--Cumulative frequency curve of specific conductance and chloride, Scuppernong River near Cresswell, (sta. 02081166 on plate 1). From Wilder and others, 1978.

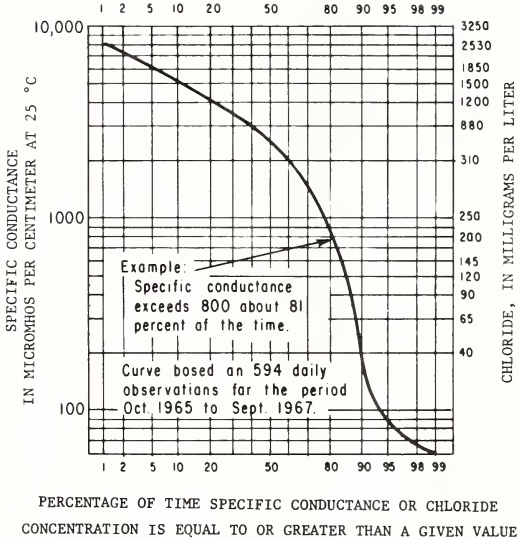


Figure 4.15.--Cumulative frequency curve of specific conductance and chloride, Scuppernong River at Columbia (sta. 02081172 on plate 1). From Wilder and others, 1978.

The information contained in these conductance duration curves should be useful in planning for possible use of these estuaries for water supply. Although the quantity of water available at most of these locations is virtually unlimited, the relations show that the water is brackish for at least part of most years. Thus, the water at these locations would then almost certainly be unsuitable for public water supplies because chloride concentrations would exceed Environmental Protection Agency recommended upper limits of 250 mg/L.

The largest cities near the sites named in 4.9 - 4.15--among them Elizabeth City, Hertford, Columbia, and Edenton--presently derive their water supplies from wells. However, industries which may in future locate in these areas and which require large amounts of water for industrial use may, depending on the industry, find estuarine water of acceptable quality at or near these locations. Although the water

quality needs of industries vary, and no criteria will fit all industries, water with a chloride concentration of 500 mg/L (as indicated by a conductance of about 1,900 μmhos) is unsuitable for many industrial uses. On the other hand, water that meets drinking water standards (less than 250 mg/L chloride) is acceptable for many uses, although some users may require treatment of the supply.

The Chowan River Estuary

The 50-mile long Chowan River, which occupies a drowned river valley, is formed by the confluence of the Blackwater and Nottoway rivers just north of the North Carolina-Virginia state line (plate 1). From here, it flows generally south and empties into the western end of Albemarle Sound near Edenton. Upstream from Holiday Island (fig. 4.16) extensive swamps border the estuary; downstream, the estuary widens considerably and is more than 2 miles wide in some sections. The average depth of the estuary is only about 12 feet. Two important tributaries, the Meherrin and Wiccacon Rivers, enter the estuary from the west.

Discharge from 3,098 mi^2 of the total of 4,943 mi^2 drainage area is gaged. From records at gaged points, the average flow of the Chowan River at the mouth is estimated at 4,600 ft^3/s, or about 0.94 $(ft^3/s)/mi^2$.

The estuary is affected to some degree by ocean tides throughout its 50-mile length, although tide ranges are less than 1 foot in most locations. The influence of ocean tides extends up into the lower parts of all tributaries to the Chowan River, including the Nottoway and Blackwater rivers (fig. 4.16 and plate 1).

Winds are usually more important than lunar tides and freshwater inflow in affecting water levels and short-term circulation in the Chowan estuary. Winds sometimes cause as much as 4 feet variation in water levels (Daniel, 1977).

Saltwater intrusion into the Chowan estuary does not occur frequently. Chloride concentrations are usually less than 50 mg/L, even at the mouth, except when unusual weather conditions force saline water out of Pamlico Sound into Albemarle Sound or when the ocean washes across the narrow barrier island at the east end of Albemarle Sound. Several factors contribute to the infrequency of saltwater intrusion under normal conditions. First, the Chowan River is far removed from the ocean; the nearest direct oceanic connection is at Oregon Inlet, about 70 miles from the mouth of the Chowan. Also, freshwater flows are sustained during dry periods by releases from reservoirs on the Roanoke River and they usually prevent saltwater from advancing into the Chowan and Roanoke estuaries.

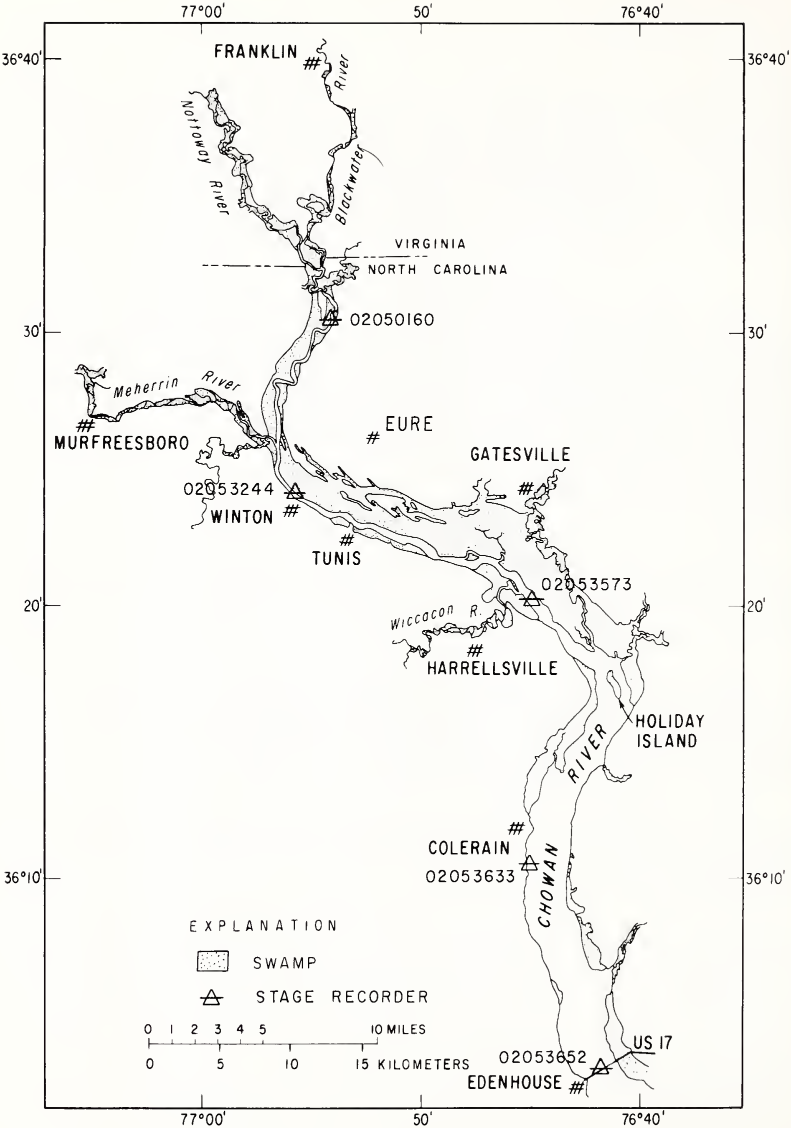


Figure 4.16.--Chowan River, major tributaries, and adjoining swamp-land. From Daniel, 1977.

Present water uses of the Chowan estuary include industrial water supplies; bathing, boating, fishing, and other forms of recreation; commercial fishing, particularly for herring, rockfish, catfish, and white perch; and agricultural uses, including livestock watering and irrigation. At present, all domestic water supplies in the North Carolina part of the basin are derived from ground water.

Algal growth in the Chowan River has at times caused severe problems. It first reached nuisance proportions in the summer of 1972, when extensive blooms severely limited the use of the river for commercial and sport fishing, recreation, and navigation. Although the Chowan River naturally contains sufficient nitrogen and other nutrients necessary for algal blooms, the rather severe conditions which existed in the summer of 1972 and again in the summer of 1976 may have been caused by increased nutrient loading from a fertilizer plant near Tunis, from municipal wastewater discharges, and from runoff from agricultural areas. The discharge from the fertilizer plant was stopped by State action soon after the 1972 bloom, but it was discovered that high nitrogen water was seeping from the ground around the plant at about the time of the 1976 bloom (Stanley and Hobbie, 1977).

Water Levels

Short-term water level changes in the Chowan estuary are caused primarily by winds, with lunar tides and freshwater inflows of lesser importance. Generally, winds from the southeast tend to cause higher water levels in the estuary, and winds from the northwest cause lower water levels, as illustrated in figure 4.17 for two locations--near Eure and near Edenhouse. Rising water levels at both locations on Dec. 7 and 8, 1974, were caused by southerly winds, and falling water levels on Dec. 9 and 10 were caused by northerly winds. The semidiurnal tide cycles are also evident in figure 4.17. Due to funnelling effects of the narrowing channel, tide ranges are actually greater at the upstream station (Eure) than at the downstream station (Edenhouse). Apparently, these funnelling effects more than compensate for the tendency of the tide wave to die out due to loss of momentum as it propogates up the estuary.

These funnelling effects are even more apparent in figure 4.18, which shows continuous water-level records for five gaging stations during a period of little wind effect on Dec. 6, 1974. The increase in tidal range in the upstream direction is apparent. As indicated by the time lag in figure 4.18, the passage of high or low tides through the estuary from the mouth near Edenhouse to near Eure, a distance of about 45.5 miles, takes about 2 hours.

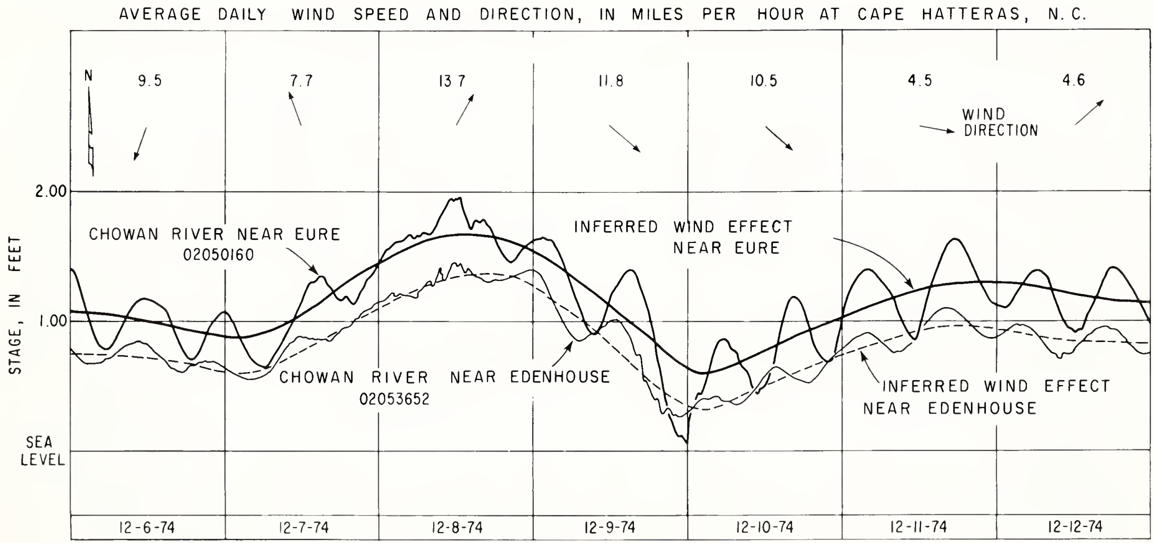
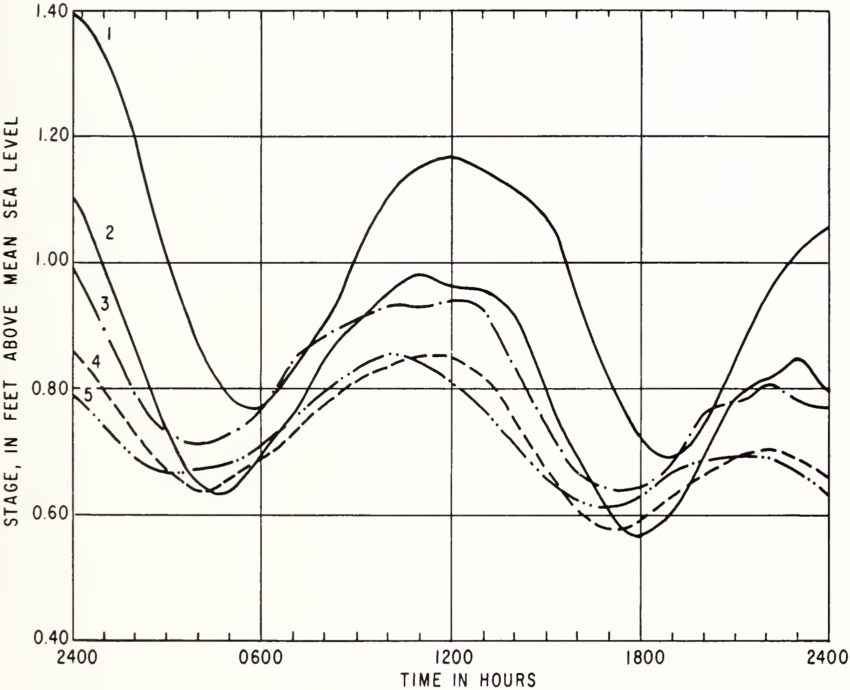


Figure 4.17.--Continuous water-level records for Chowan River near Eure and Chowan River near Edenhouse for December 6-12, 1974. From Daniel, 1977.



STATION NAME AND NUMBER	RIVER MILES ABOVE CHOWAN RIVER NR EDENHOUSE	RIVER WIDTH IN FEET
1. Chowan River nr Eure 02050160 (FIG. 4.16)	45.46	480
2. Chowan River at Winton 02053244	35.49	800
3. Chowan River nr Harrellsville 02053573	22.29	1620
4. Chowan River nr Colerain 02053633	11.38	8900
5. Chowan River nr Edenhouse 02053652	0.00	8650

Figure 4.18.--Continuous water-level records for five gaging stations on the Chowan River for December 6, 1974. From Daniel, 1977.

Analysis of water-level data from an earlier study at the same two locations (Jackson, 1968) reveals an interesting annual cycle in water levels (fig. 4.19). Monthly average water levels in the Chowan River estuary near Eure and Edenhouse follow a sine-like pattern, with highs in the summer and lows in the winter. This is nearly the opposite of the effects of normal runoff patterns in upland streams, which produce high water levels in late winter and early spring and low water levels in the summer and fall. The annual water-level pattern in the Chowan estuary was attributed by Daniel (1977, p. 32) to the seasonal pattern of the prevailing winds in the area, which are generally out of the north and northwest in the fall and winter, resulting in lower water levels, and out of the south and southwest during the summer, resulting in higher water levels. The seasonal range in water levels thus produced is about 0.8 foot at both stations.

Flow

Usually, short-term flow in the Chowan estuary is influenced primarily by winds, lunar tides, and freshwater inflow, in that order of importance. Only during periods of high runoff is freshwater inflow of greater significance than lunar tides and winds at a given moment. Long-term flow is, however, determined primarily by the rate of freshwater inflow.

Freshwater inflow to the estuary from all sources averages about 4,600 ft^3/s [0.94 $(ft^3/s)/mi^2$] and the estimated monthly distribution of average inflow, in cubic feet per second, is as follows:

Jan. - 6,500	Apr. - 6,600	July - 3,000	Oct. - 2,200
Feb. - 9,100	May - 3,700	Aug. - 3,500	Nov. - 2,500
Mar. - 8,600	June - 2,600	Sept.- 3,000	Dec. - 4,400

Variability in annual mean inflows (fig. 4.20) is caused primarily by year-to-year variations in precipitation. Although the relation in fig. 4.20 was developed on a per-square-mile basis for the combined drainage of 2,060 mi^2 represented by the Blackwater River near Franklin, Va., and the Nottoway River near Sebrell, Va., the relation may be applied with useful accuracy to the entire 4,943 mi^2 drainage area of the Chowan River basin.

Periods of low freshwater inflow to the Chowan estuary are of great interest because these are times of critical water supply and because the lack of flushing of the river at such times is one of the conditions that favors nuisance algal blooms. Fig. 4.21 shows combined low-flow frequency curves for the Blackwater River near Franklin, Va., and the Nottoway River near Sebrell, Va.

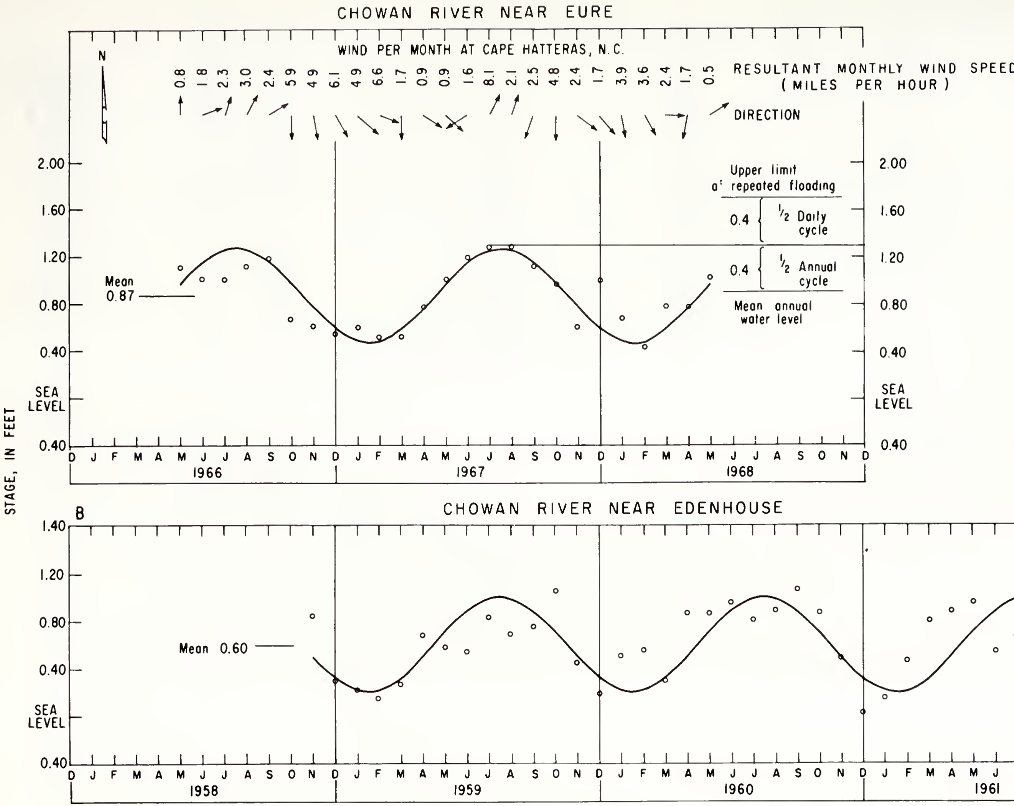


Figure 4.19.--Monthly average stages for Chowan River near Eure and Chowan River near Edenhouse. The solid lines are sine curve approximations of the annual cycle of water levels. From Daniel, 1977.

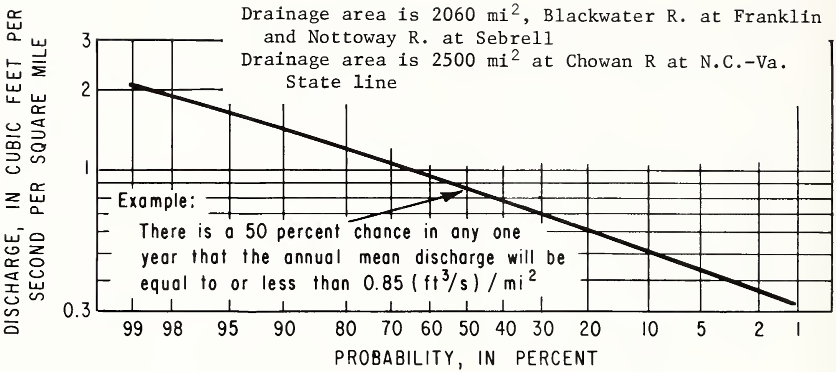


Figure 4.20.--Frequency curve of annual mean discharges, combination of Blackwater River at Franklin, Va., and Nottoway River near Sebrell, Va. From Wilder and others, 1978.

Some low-flow regulation does take place on tributaries to the Chowan estuary. Union Camp Paper Company, which utilizes ground water for its process water, did at one time discharge pulp mill wastes into the Blackwater River continuously, but since 1964 waste water has been stored and discharges limited to winter months only, when freshwater inflows are high. However, the city of Norfolk, Va., does divert some water from the Blackwater and Nottoway rivers to augment its municipal supply, but the effects of these diversions on low flows in the Chowan River have not yet been evaluated.

Daniels (1977) discussed a one-dimensional deterministic flow model of the Chowan River based on the continuity equation. The model was developed by the Geological Survey to generate estimates of daily flow through a number of river segments for use in a water quality management model. The outflow from each segment was computed from an expanded form of the continuity equation:

$$Q_i = Q_{i-1} + I_i + P_i - E_i - ET_i \pm \Delta S_i \tag{4.1}$$

where Q_i is the outflow from segment i; Q_{i-1} is outflow from the adjacent upstream segment; I_i is the lateral inflow from the ungaged drainage area apportioned to segment i, exclusive of the drainage area

within segment i; P_i is the precipitation that falls directly on segment i; E_i is the evaporation from the open water surface in segment i; ET_i is the evapotranspiration from the swampland in segment i; and ΔS_i is the change in storage in segment i (a falling stage contributes to a positive Q_i). Once calculated, the outflow, Q_i, from any segment becomes the inflow, Q_{i-1}, to the next downstream segment. Because flows within the Chowan and the lower reaches of its tributaries are tide-affected, flows occur in both upstream and downstream directions. By convention, upstream flow is indicated by a negative sign; downstream flow is positive.

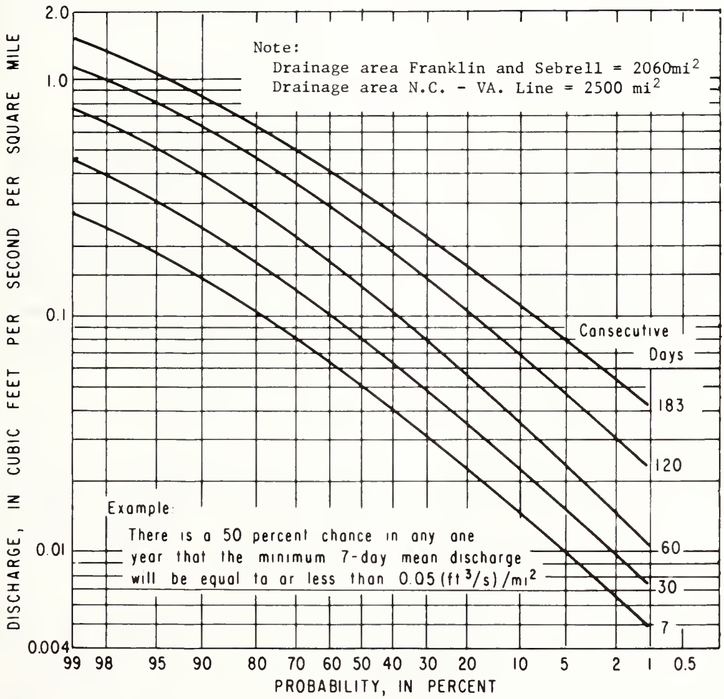


Figure 4.21.--Low-flow frequency curves of annual lowest mean discharge for indicated number of consecutive days, combination of Blackwater River at Franklin, Va., and Nottoway River at Sebrell, Va. From Wilder and others, 1978.

Summaries of generated flows through two of the segments are shown in figure 4.22 for the period April 1974 through March 1976. At Eure, the most upstream station, minimum daily average discharges for each month were often near zero, but no large net upstream flows occurred. Near Edenhouse, at the mouth, the minimum daily average discharge for each month was upstream for all months except one. This is indicative of the increasing influence of wind and lunar tides in the more downstream segments of the Chowan estuary.

The average discharge at the mouth near Edenhouse for the two-year period was calculated to be 5,800 ft^3/s, or about 26 percent greater than the long-term estimated average discharge of 4,600 ft^3/s. Above-average discharge was expected because of above-average rainfall for the April 1974-March 1976 period.

Water Quality

Chowan River water at times is highly turbid due to suspended material and is strongly colored from humic material. A maximum color unit value of 320 has been measured at the Chowan River at Winton (station 02053244 in table 4.4), which far exceeded the 75 units recommended by the Environmental Protection Agency (1976) as an upper limit for drinking water. Iron may also be a problem at times, with values sometimes exceeding the 0.3 mg/L recommended upper limit given in the same report. However, with proper treatment, water from the Chowan Estuary is, where not contaminated or mixed with saltwater, of acceptable quality for public, agricultural, and industrial use.

Salinity

The Geological Survey operated specific conductance stations on the Chowan River for various time periods at three locations--near Eure, at Winton, and near Edenhouse (table 4.3 and plate 1). To supplement this point data, seven boat runs to determine specific conductance at a number of other locations were made between October 7, 1954, and September 27, 1968.

These data show that saltwater intrusion in the Chowan River occurs infrequently. The specific conductance at Edenhouse, for example, exceeds 800 μmhos only about 18 percent of the time (fig. 4.12); upstream at Winton and near Eure, the time percentages would be much less. The maximum specific conductance near Eure for the period October 1967 through December 1968, a period of continuous record, was 880 μmhos on December 19, 1967. Although this period of record was short, discharges were much below average. Thus, it is likely that the maximum upstream extent of saltwater intrusion in the Chowan estuary under non-hurricane conditions would be near Eure. This conclusion is strengthened by the

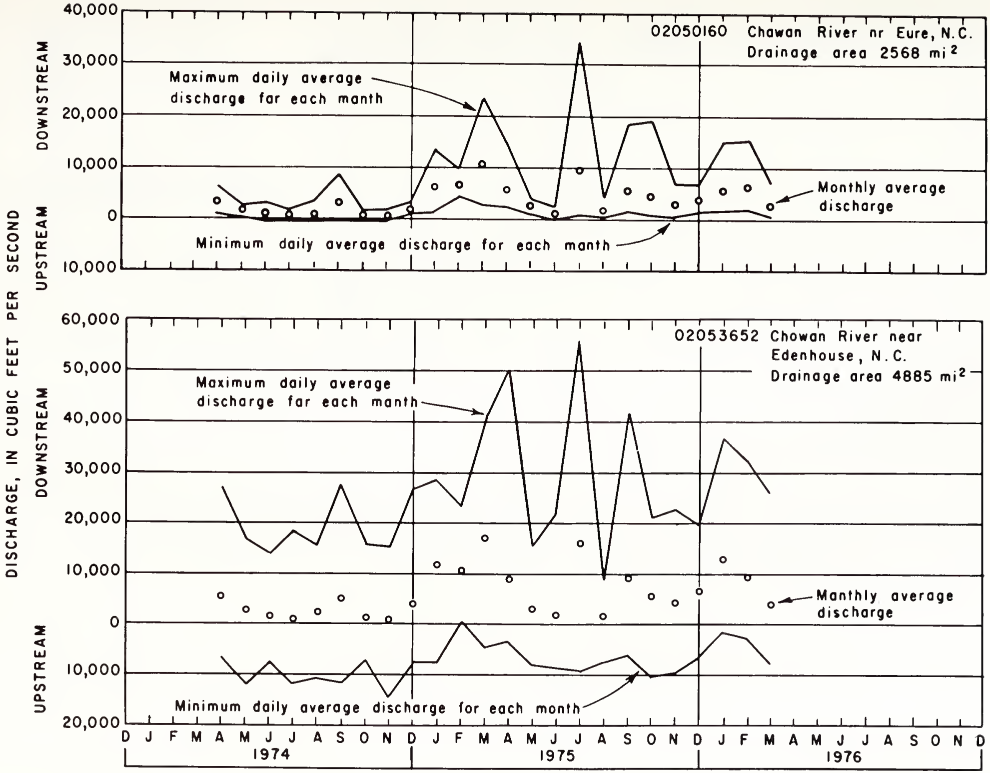


Figure 4.22.--Monthly average discharge and maximum and minimum daily average discharge for each month of Chowan River near Eure and Chowan River near Edenhouse. From Daniel, 1977.

Table 4.4.--Summary of chemical analyses of water samples collected at key stations in the Chowan River basin. Chemical constituents are in milligrams per liter, except specific conductance, pH, and color. Adapted from Wilder and Slack, 1971a.

Station number	Station name	Drainage area in mi^2	Period of sampling	Sampling frequency	Extreme and average	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids: Residue at 180°C	Dissolved solids: Calculated	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Non-carbonate	Specific conductance (Micromhos at 25°C)	pH	Color units
	CHOWAN RIVER BASIN																							
02053073	Meherrin River near Severn, N.C.	about 1,120	Sept. 1954 to Sept. 1955	monthly	Max	17	0.77	13	3.2	14	4.0	83	20	6.8	0	2.3	....	105	....	46	9	166	7.1	60
					Min	9.9	.03	4.2	1.0	4.1	1.3	8	2.9	3.0	0	.0	....	61	....	15	0	62	5.7	10
					Avg	13	.22	6.3	1.9	7.6	1.9	31	9.8	4.7	0	.7	....	73	....	24	1	96	.....	30
02052244	Chowan River at Winton, N.C.a/	about 4,200	Oct. 1954 to Sept. 1967	daily	Max	17	.64	11	2.8	47	3.1	84	16	46	.7	3.5	0.20	188	171	36	10	297	7.7	320
					Min	.4	.01	2.9	.5	2.5	.9	11	1.7	2.9	.0	.0	.00	40	34	10	0	36	6.0	25
					Avg	10	.20	5.7	1.6	9.3	1.7	25	5.6	9.6	.2	1.4	.10	73	65	21	2	93	.....	73

a/ Subject to occasional saltwater encroachment during prolonged periods of low streamflow or unusually high ocean tides. Records for periods of saltwater encroachment not included for summary purposes.

fact that the maximum specific conductance observed at the more downstream station, Winton, was only 1,400 μmhos (398 mg/L of chloride) during 13 years of daily sampling (October 1954-September 1967).

At low salinity, mixing is fairly complete from top to bottom across the Chowan estuary, although instantaneous salinity at such times may be significantly less or more close to the banks or in the adjacent swamps because water moves more slowly there than in the middle sections of the river. Thus, at high-water slack tide, salinity may be less near the channel edges than elsewhere. Conversely, during low-water-slack tide, salinity may be higher near the channel edges than elsewhere.

At higher salinity, stratification becomes more apparent. Notice from figure 4.12 that the frequency curves for surface and bottom specific conductance seem to merge at values less than about 800 μmhos, while they diverge at higher values, indicating stratification.

The inverse relation of salinity at Edenhouse to freshwater discharge is evidenced by the percent of time bottom conductance values exceeded 800 μmhos during the prevailing annual average discharges for the years 1958-67 (fig. 4.23). Although the relation may be useful for preliminary estimates of bottom specific conductance conditions at Edenhouse under various conditions of annual freshwater inflow, it must be acknowledged that the data points have considerable scatter around the line of relation. This scatter may be due to several factors--the differences in within-year distribution of discharges, year to year differences in prevailing wind speed and direction, and variations in regulation patterns of reservoirs on the Roanoke River which, as previously mentioned, have a direct influence on moderating saltwater intrusion in Albemarle Sound and, indirectly, into the Chowan River.

The Roanoke River Estuary

The total area of the Roanoke River basin (plate 1) is 9,666 mi^2, the largest of any North Carolina estuary. However, only 3,506 mi^2 of the drainage lies in North Carolina; the other 6,160 mi^2 are in southern Virginia. The Roanoke River heads in the Valley and Ridge Province west of Roanoke, Virginia, and flows in a general southeasterly direction toward the Atlantic Coast, emptying into Albemarle Sound about 7 miles downstream from Plymouth, North Carolina. Principal tributaries include the Dan, Falling, Otter, and Blackwater Rivers. The limit of lunar tide effects in the Roanoke River has not been well established, but is thought to be near Hamilton, about 60 miles upstream from the mouth.

The greatest width of the estuary, near the mouth, is only about 0.3 mile and, upstream from Plymouth, widths are about 0.1 mile or less. The narrow width of the Roanoke near the mouth is in sharp contrast to the Neuse, Pamlico, and Chowan rivers which are several miles wide at

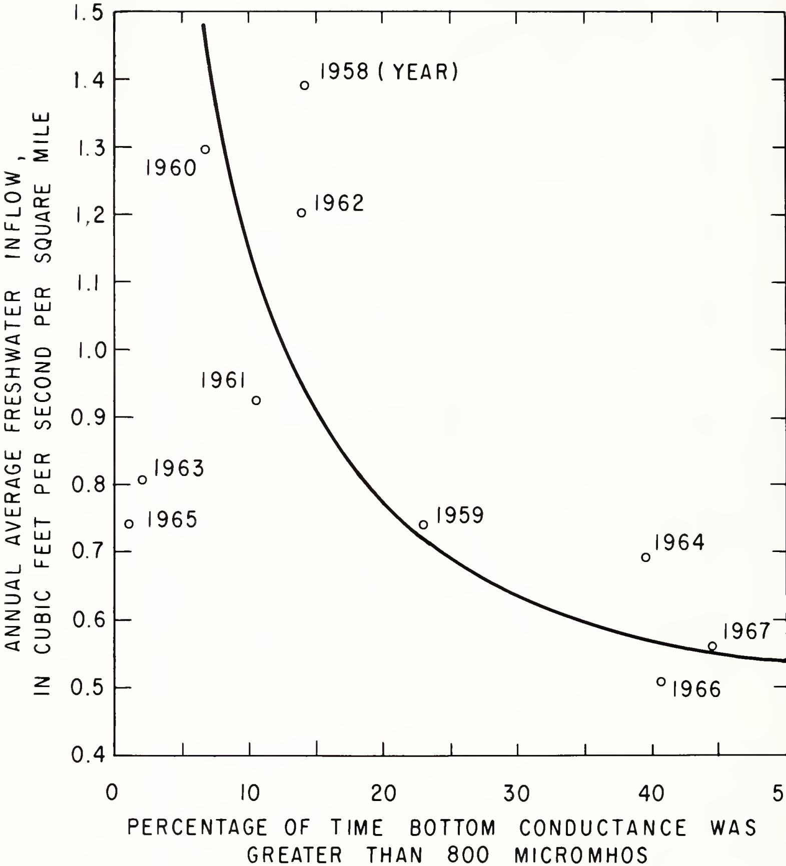


Figure 4.23.--Percentage of time bottom specific conductances exceeded 800 micromhos for various annual average discharges for Chowan River at Edenhouse, 1958-67.

their mouths. The lower Roanoke, like the others are now, was once a drowned river valley. Now, however, it has been largely filled by sediments. Within the delta thus formed is a fairly unusual system of distribitaries (fig. 4.24) which carry some water from the Roanoke into the Cashie River and, in the case of one large unnamed distributary, directly into Albemarle Sound. Maximum depths along the estuary vary from about 8 to 18 feet. A commercial navigation channel is maintained in the Roanoke River to Palmyra, 81 miles upstream from the mouth. The channel is maintained to 12 feet deep and 150 feet wide from Albemarle Sound to about 1 mile upstream from Plymouth, a distance of 10 miles; thence a channel 8 feet deep and 80 feet wide to Palmyra, a distance of 18 miles.

Average annual precipitation over the basin is about 45 inches. The average annual outflow of the Roanoke River at the mouth is about 8,900 ft^3/s, second only to the outflow of the Cape Fear River among North Carolina's estuaries.

Flow of the Roanoke River is highly regulated, particularly by Roanoke Rapids Lake (details to be discussed later). The combination of relatively high outflow, small cross-sectional areas, and low-flow augmentation by Roanoke Rapids Lake, effectively blocks saline water from the estuary. During 13 years (Oct. 1954 - Sept. 1967) of daily water sampling at Jamesville (sta. 02081094 on plate 1), the maximum measured chloride concentration was only 12 mg/L. Three specific conductance surveys by the Geological Survey during normally low-flow periods (10-6-54, 7-25-57, and 10-1-57) failed to reveal any significant saltwater encroachment, even at the mouth. Significantly, the survey of October 6, 1954, was made before increased low-flow augmentation from Roanoke Rapids Lake and at a time of record low streamflows in many parts of the State. At that time, near maximum-of-record saltwater encroachments were being measured on other estuaries. Thus, it is not likely that any significant saltwater encroachment will occur in the future in the Roanoke River estuary, even under extreme drought conditions, as long as the current flow regulation patterns are maintained.

Flow

Flow in the Roanoke River estuary has not been studied in detail; thus it is not really known what role winds play in the flow or to what extent the flow is affected by tides. We can infer that winds and tides play a lesser role here than in any other major North Carolina estuary because of the relative narrowness of the channel and the lack of significant funnelling effects. Conversely, we can infer that freshwater discharges play a relatively larger role because of the greater magnitude of the discharges in relation to channel cross-sectional areas. However, validation of these inferences awaits confirmation from water-level records and flow measurements.

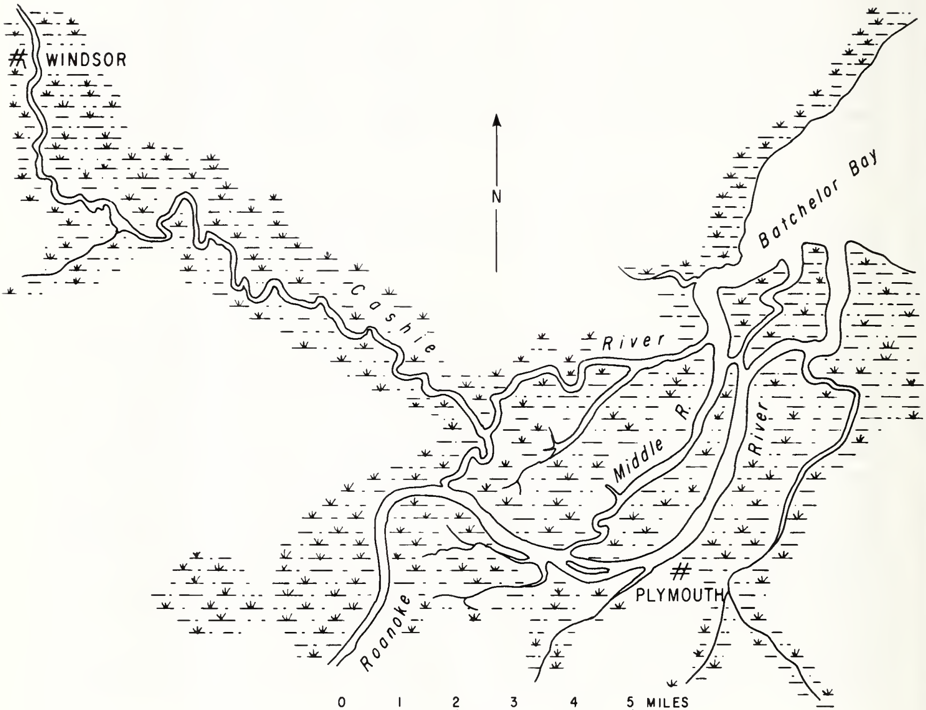


Figure 4.24.--Distributary system of the lower Roanoke River.

As previously mentioned, the average annual outflow of the Roanoke River at the mouth is about 8,900 ft^3/s, or about 0.92 (ft^3/s) mi^2, but average flows for a given year may range from about 0.50 to 1.50 (ft^3/s) $/mi^2$ (fig. 4.25). Actually, discussion of freshwater inflow to or outflow from the Roanoke River estuary is not really meaningful except within the context of a knowledge of the existing patterns of flow regulation. Flow of the Roanoke River is extensively regulated by Philpott Lake, John H. Kerr Reservoir, Roanoke Rapids Lake, Leesville Lake, Lake Gaston, and Smith Mountain Lake. All of these reservoirs were created primarily for hydroelectric power generation, but many also provide for flood control, low-flow augmentation, water supply, and recreation. Because it is the most downstream of these reservoirs, Roanoke Rapids Lake is most important from the point of view of its effects on flow in the Roanoke estuary. Pursuant to its license from the Federal Power Commission, the Virginia Power and Electric Company must maintain, subject to special provision, minimum instantaneous flow releases from Roanoke Rapids Lake (drainage area 8,395 mi^2) according to the following schedule:

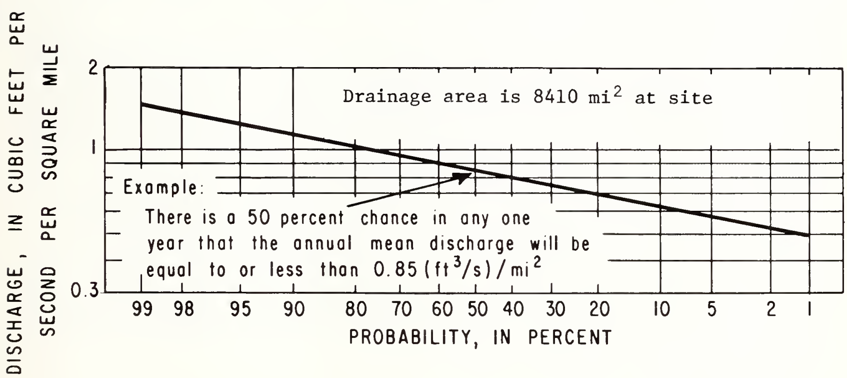


Figure 4.25.--Frequency curve of annual mean discharges of Roanoke River at Roanoke Rapids. After Wilder and others (1978).

Month	Minimum instantaneous flow, in cubic feet per second
January, February, March	1,000
April	1,500
May - September	2,000
October	1,500
November, December	1,000

Usually, actual releases from Roanoke Rapids Lake far exceed these minimum requirements, as indicated by measured flows of the Roanoke River at Roanoke Rapids (sta. 02080500 in plate 1). Given below, in cubic feet per second, are estimated average monthly outflows at the mouth of the Roanoke River estuary for the period October 1965 - September, 1975. About 87 percent of these flow amounts are accounted for by controlled releases from Roanoke Rapids Lake:

Jan. - 10,000	Apr. - 11,000	July - 8,000	Oct. - 6,500
Feb. - 12,000	May - 10,000	Aug. - 7,500	Nov. - 7,500
Mar. - 10,000	June - 8,500	Sept. - 6,500	Dec. - 8,300

The effects of high-flow regulation are reflected in the similar averages for January - May; flood flows are stored in the various reservoirs and released over long periods of time. Low-flow augmentation is apparent from the relatively high August - November flows; they average about 0.72 $(ft^3/s)/mi^2$ compared to only about 0.57 $(ft^3/s)mi^2$ in the unregulated Chowan River estuary for the same months.

The effects of flow regulation are also apparent in the low-flow frequency curves of fig. 4.26 for the Roanoke River at Roanoke Rapids. At lower probabilities of occurrence, the consecutive-day low flows at Roanoke Rapids are much higher on a per-square-mile basis than are those, say, of the Blackwater and Nottoway Rivers (fig. 4.21); also, the expected range of values for a given consecutive-day discharge is much less for the Roanoke Rapids station.

Water Quality

Summaries of the chemical quality of water at four key sites in the Roanoke River basin are given in table 4.5, including observed ranges and average values of major chemical constituents. Iron concentrations sometimes exceed the 0.3 mg/L upper limit recommended by the Environmental Protection Agency (1976) for public water supplies, but iron can be removed easily with treatment. Color sometimes exceeds the recommended upper limit given in the same report of 75 color units at all stations except Roanoke Rapids. Downstream from Roanoke Rapids, color

increases in the Roanoke River due to inflows from swampy areas, which impart color from decaying vegetation and the leaching of humic acids. The Cashie River, in this regard, is typical of streams draining coastal swamp areas in the lower half of the Roanoke River basin, where even average color values may exceed recommended upper limits (table 4.5).

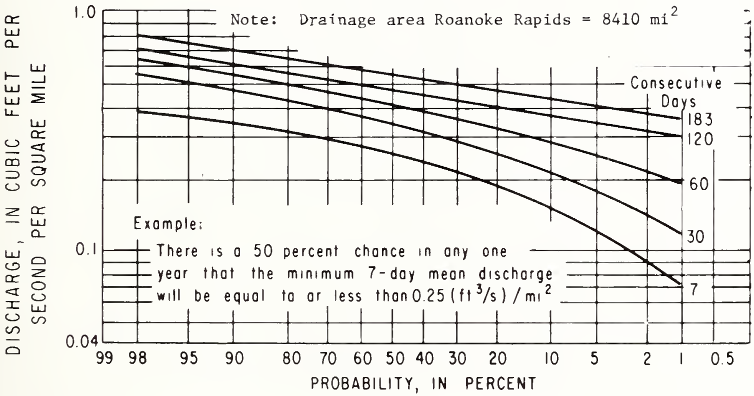


Figure 4.26.--Low-flow frequency curves of annual lowest mean discharge for indicated number of consecutive days, for Roanoke River at Roanoke Rapids. After Wilder and others, 1978.

Table 4.5.--Summary of chemical analyses of water samples collected at key stations in the Roanoke River basin. Chemical constituents are in milligrams per liter, except specific conductance, pH, and color. Adapted from Wilder and Slack, 1971a.

Station number	Station name	Drainage area in mi^2	Period of sampling	Sampling frequency	Extreme and average	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids: Residue at 180°C	Dissolved solids: Calculated	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Non-carbonate	Specific conductance (Micromhos at 25°C)	pH	Color
02080500	Roanoke River at Roanoke Rapids, N.C.	8,410	Oct. 1948 through Sept. 1967	daily	Max	17	.59	25	3.9	20	2.6	110	24	9.9	.5	2.2	.10	74	117	73	3	206	7.8	45
					Min	6.5	.00	4.9	1.6	3.1	.7	23	4.0	2.0	.0	.1	.00	46	50	19	0	60	6.4	3
					Avg	13	.06	6.6	2.6	6.0	1.4	34	6.3	3.5	.1	.6	.02	58	64	27	0	83	...	7
02081000	Roanoke River near Scotland Neck, N.C.	8,700	Oct. 1944 through Sept. 1967	daily	Max	16	3.3	13	5.9	17	13	131	12	19	.4	5.2	.10	173	78	57	1	155	7.4	80
					Min	6.2	.00	4.8	1.2	4.5	1.4	11	1.2	1.0	.0	.0	.00	47	44	18	0	68	6.1	5
					Avg	11	.13	8.4	2.4	9.0	3.0	45	7.9	5.7	.1	1.5	.02	78	63	31	0	118	...	19
02081094	Roanoke River at Jamesville, N.C.	about 9,250	Oct. 1954 through Sept. 1967	daily	Max	14	.59	15	4.1	14	3.6	72	12	12	.5	5.9	.23	98	83	52	4	188	7.7	90
					Min	2.8	.00	4.0	.5	3.7	.6	17	2.0	2.8	.0	.3	.00	35	33	12	0	55	6.2	5
					Avg	8.7	.10	8.6	2.5	8.0	2.1	40	6.9	6.1	.1	2.1	.06	72	67	31	0	105	...	30
02081122	Cashie River at Windsor, N.C.	179	Oct. 1961 through Sept. 1967	monthly	Max	23	.80	11	3.1	28	4.8	60	34	23	.4	1.7	.50	129	115	37	32	203	6.9	160
					Min	1.5	.00	2.2	.5	1.6	.9	5	2.6	2.0	.0	.3	.00	49	22	10	0	34	5.3	20
					Avg	8.3	.19	5.1	1.4	8.2	2.0	20	8.2	9.1	.2	.9	.05	77	49	18	5	82	...	81

SUMMARY AND DISCUSSION

The Cape Fear River and the Northeast Cape Fear River are the only major North Carolina estuaries having relatively direct ocean connections. As a result, tidal ranges there are several feet in most places and the movement of saltwater in and out of these estuaries is very sensitive to tides and changing freshwater inflows. However, the estuary portions of the Neuse-Trent, Tar-Pamlico, Chowan, and Roanoke River systems are semi-enclosed by the Outer Banks and are subject to the tide-dampening effects of Pamlico and Albemarle Sounds. As a result, tidal ranges there are less than 0.5 foot in most places and salinities change much more slowly in response to changing freshwater inflow.

In the Cape Fear River and Northeast Cape Fear River estuaries, short-term flow is dominated in most locations by ocean tides, followed in importance by freshwater inflow and winds. In Pamlico Sound, Albemarle Sound, and all other major estuaries, with the probable exception of the Roanoke, winds are usually the dominant short-term current-producing force, followed in importance by ocean tides and freshwater inflow.

The average annual outflow from the 9,140 mi^2 area comprising the Cape Fear River basin is about 11,100 ft^3/s. Pamlico Sound, having a surface area of about 2,060 mi^2, receives direct drainage from a 12,520 mi^2 area (including the area of the sound). In addition, it receives indirect drainage through Croatan and Roanoke Sounds from the Albemarle Sound system (18,380 mi^2). The average flow from this 30,900 mi^2 area is about 32,000 ft^3/s. Of this amount, about 17,300 ft^3/s is contributed by the Albemarle Sound system.

Flow in the Cape Fear River is affected by ocean tides upstream to Lock 1, about 65 miles upstream from its mouth. In the Northeast Cape Fear River, tides extend to about 50 miles upstream from Wilmington. Measurements in the Cape Fear River estuary near Phoenix indicate that reversals of flow during tidal cycles are the rule rather than the exception; only when the freshwater outflow near Phoenix is greater than about 13,000 ft^3/s are upstream flows during flood tides prevented. For the single series of measurements available in the Northeast Cape Fear estuary on Oct. 23, 1969, a freshwater outflow of about 22,000 ft^3/s at the measuring site 6.4 miles upstream from the mouth would have been required to prevent flow reversal.

Reliable measurements of tide-affected flow over tidal cycles have not been made on other major North Carolina estuaries, but the upstream limits of tide effects have been fairly well established. Ocean tides affect the Neuse River upstream to Fort Barnwell, about 63 miles from the mouth. They affect the Trent River upstream to Pollocksville, about 57 miles upstream from the mouth of the Neuse River. The upstream limit

of tide effects in the Tar River is near Greenville, about 57 miles upstream from the mouth of the Pamlico River. In the Roanoke River, it is thought that the upstream limit of tide effects is near Hamilton, about 60 miles from the mouth. The Chowan River estuary is affected by ocean tides throughout its 50-mile length.

Freshwater entering the major estuaries is generally, where not contaminated, of suitable quality for public supply and most industrial uses. In some estuaries, however, iron sometimes exceeds the 0.3 mg/L recommended upper limit (Environmental Protection Agency (1976) for drinking water, and highly-colored water from swamp drainage may exceed the 75 color unit recommended upper limit. Algal blooms sometimes reach nuisance proportions in several estuaries, particularly the Neuse, Pamlico, and Chowan Rivers, where nutrients are usually abundant.

All major North Carolina estuaries except the Roanoke River are subject to at least occasional intrusion of saltwater. Maximum upstream advances of the saltwater front (200 mg/L chloride) occur as a result of extended periods of low freshwater inflow or, occasionally, upstream currents driven by hurricane-force winds. In fact, the maximum-of-record upstream saltwater intrusion for most North Carolina estuaries occurred during or in the aftermath of the passage of Hurricane Hazel on Oct. 15, 1954.

The maximum known upstream intrusion of the saltwater front in the Cape Fear River was to about 20 miles upstream from Wilmington; in the Northeast Cape Fear River, to about 23 miles upstream from Wilmington; in the Neuse River, to about 2.2 miles northeast of Ft. Barnwell; in the Trent River, to about 4.5 miles upstream from Pollocksville; in the Tar River, to about 20 miles upstream from the mouth; and in the Chowan River, to near Eure. All these intrusions were for hurricane conditions, except those for the Neuse and Chowan Rivers, which are based on non-hurricane low-flow conditions.

Data on shoaling rates and sediment transport from upstream sources for the Cape Fear and Northeast Cape Fear Rivers show that upstream sources can only account for a small proportion of new shoaling materials found in the lower channelized reaches--most of it must be derived from slumping along channels, from nearby shore erosion, from old spoil areas, or possibly from ocean sediments carried upstream by near-bottom density currents. Not enough data is available from other estuaries discussed in this report to determine whether or not this conclusion holds true elsewhere.

It is appropriate here at the end of the report to observe that there are yet a number of deficiencies in our knowledge of even the basic hydrology of North Carolina's estuaries and sounds and that some of the more complex physical, chemical, and physiological processes at work in them are far from being adequately understood or defined. Among

the deficiencies in basic knowledge are 1) lack of measurements of tide-affected flow and circulation patterns in most estuaries 2) a general lack of knowledge of movement and dispersion characteristics of contaminants which may be accidentally spilled into the estuaries, 3) a lack of chemical analyses other than salinity for waters in the central area of Pamlico Sound and in many small, but important estuaries serving as fish nurseries, and 4) a lack of reliable models to predict salinity advances under various conditions of freshwater inflow and tides. Among deficiencies in understanding of the more complex hydrologic phenomena are 1) lack of knowledge of the fate of nutrients and pesticides in runoff from agricultural runoff which enters the estuaries and sounds, 2) a lack of knowledge of the sources and methods of transport and deposition of sediment in many estuaries, 3) inadequate knowledge of hydrologic conditions which may contribute to (or prevent) destructive algal blooms, 4) poor definition of runoff from canals draining agricultural areas along the coast, and of the effects of changed runoff patterns in those areas on fishery resources, 5) inadequate understanding of the possibly major role of bottom sediments in acting as a trap for nutrients, pesticides, and trace metals entering the estuaries and sounds and, 6) lack of detailed knowledge of the effects of winds on water levels, circulation, and mixing in estuaries and sounds.

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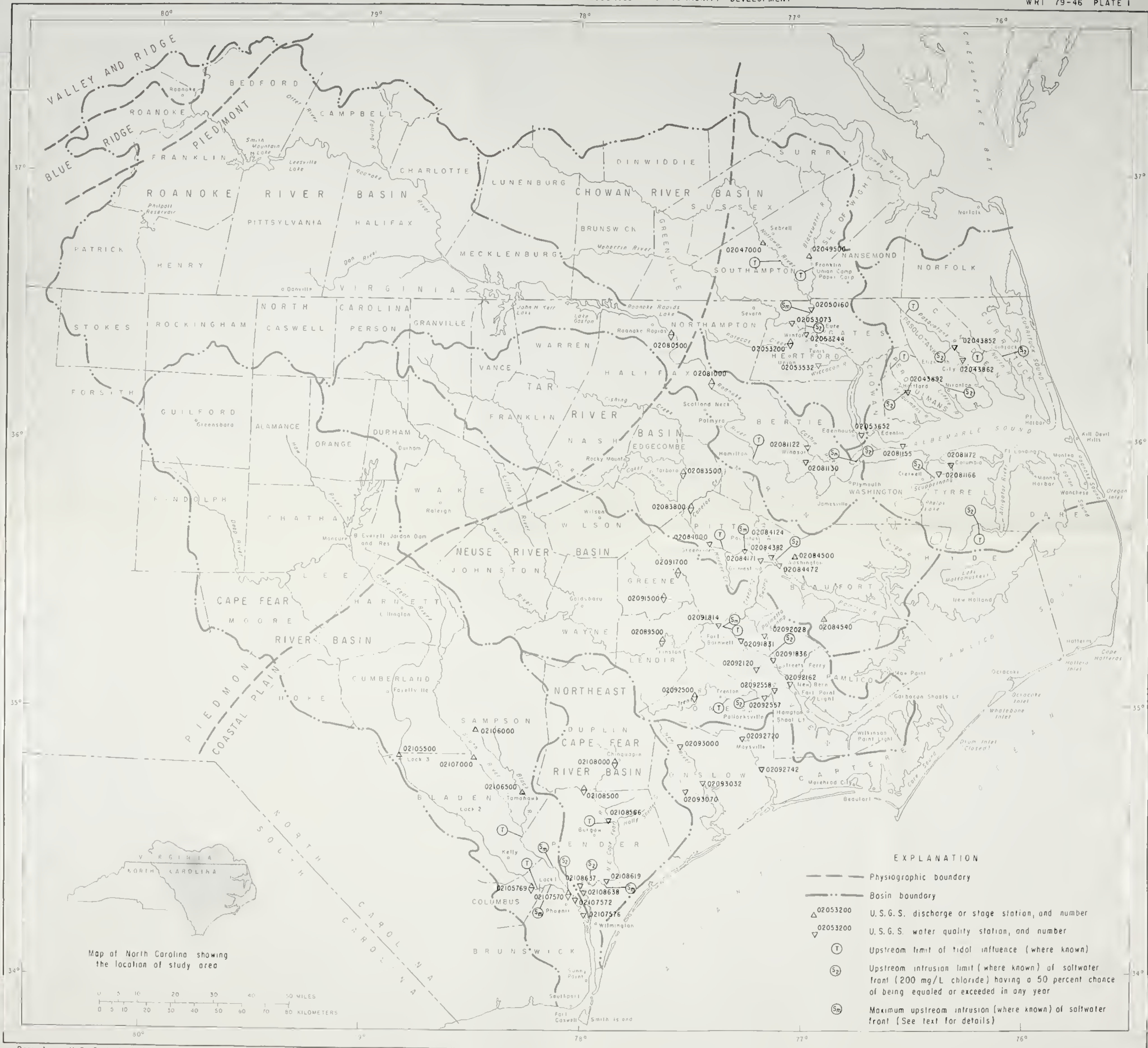
U. S. Government Printing Office: 1979-643-876



Base from U. S. Geological Survey
State base map, 1975

PLATE 1. MAJOR ESTUARIES AND SOUNDS OF NORTH CAROLINA

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